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Gasoline Rationing and Gasoline Shortages Effects on Misfueling

Institute for Defense Analyses
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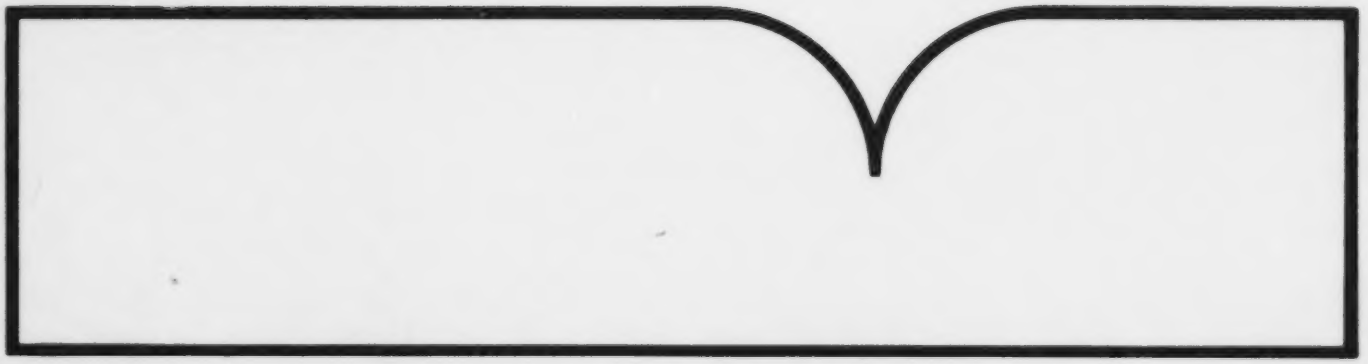

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R. G. Oliver

October 1980

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INSTITUTE FOR DEFENSE ANALYSES
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16. Abstracts

This paper considers misfueling (use of leaded gasoline in cars calling for unleaded) induced under fuel-short conditions, and its prevention, without and with rationing in place, according to the plan passed by Congress in July of 1980. It is shown, as would be expected, that shortage-induced misfueling would be greatly reduced by a policy in which the ratio of leaded to unleaded gasoline delivered is kept slightly below that demanded. The rationing plan is examined for possible inadvertent means by which misfueling might be induced; one feature of the plan, in particular, that which excludes the alcohol component of gasohol from rationing, appears to be ill-advised, as it would induce an artificial demand for and shortage of unleaded, with forced misfueling as a probable consequence. Motorist behavior during rationing is difficult to predict; much depends on public acceptance. In general, the nation's large investment in catalysts can be protected only by maintaining awareness of unleaded-leaded issues during emergency planning.

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Prof. George Daly, University of Houston
Dr. Howard Margolis, Massachusetts Institute of Technology
Prof. Henry Steele, University of Houston
Prof. J. Eugene Webb, Stanford University

This group provided fresh viewpoints, creative concepts, and constructive criticism of suggestions put forth for discussion by this author.

Special acknowledgement and thanks are also due to Mr. Richard Kozlowski, (then) Acting Deputy Assistant Administrator for Mobile Source, Noise and Radiation Enforcement at EPA, who described EPA's concerns in these matters to the group, and to Mr. Andrew Fang, of DOE, who described the rationing plan and answered many questions as to its details.

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The paper as it stands is, of course, entirely the responsibility of the author.

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SUMMARY

The standby gasoline rationing plan submitted by the Carter Administration to the Congress on June 12, 1980, since passed, and now in a pre-implementation study phase, provides a framework for distributing gasoline in the event of a rather severe (> 20 percent) gasoline shortage. The plan distributes gasoline on the basis of registered vehicles (encouraging old vehicle retention) and permits sales of ration rights in a "white" market. This plan, and indeed any procedure proposed for use in the event of gasoline shortages, must be carefully examined for possible adverse effects, particularly with regard to the possibility that it may inadvertently induce misfueling (use of leaded gasoline) in catalyst-equipped cars; such misfueling degrades catalysts and increases automotive emissions. IDA was asked by EPA, in connection with IDA's EPA-sponsored studies on misfueling, to examine the rationing plan for any such adverse effects. This paper thus centers around the rationing plan, but considers shortage-induced misfueling generally; it also suggests means by which possible adverse effects during shortages might be avoided, and treats a number of related issues.

This paper, as is commonly done currently, in large measure treats leaded and unleaded gasoline as entities, with the splits between grades and the octane levels involved given only secondary attention. The reality is more complex: misfueling, in general, involves octane factors, relative shortages (which are affected by price controls), and price differentials, all of which may be affected by regulations which may be in place or imposed. These factors cannot all be anticipated, but some comments are included.

Principal results and observations follow:

1. *In principle, shortage-induced misfueling is random in nature and cumulative in its impact;* large numbers of catalysts can be affected in a relatively short time. *Shortage-induced misfueling can thus be more serious than is misfueling for price-differential or performance reasons.*

2. *Shortage-induced misfueling can occur only when unleaded fuel is not available and leaded is available. It follows that under supply-short conditions misfueling due to shortage can be largely prevented by the "simple" expedient of maintaining relative deficits of leaded gasoline (vs the theoretical demand-ratio), so that leaded gasoline tends to disappear first from the market place.* The necessary relative surplus of unleaded is small (probably under 5 percent) without rationing and probably smaller with rationing, as rationing *should* (if carefully carried out and perceived as being equitable) permit more orderly markets. Public pressures would, however, call for the converse, i.e., relaxation of lead phase-out rules, to permit more *total* gasoline to be marketed; responses should be ready. Refining capacity projections included herein suggest that capacity should be adequate, over the next several years, to maintain the needed relative unleaded surplus, assuming surprises in demand ratio or inadvisable policies (number 3 below) are not encountered or implemented.

Supplies of unleaded can be increased by reducing the average octane number. This approach is deemed to be undesirable as it may induce those customers who normally use unleaded premium, should it be unavailable, to switch to leaded regular at 89 octane rather than to unleaded regular, if at 87. Leaded premium is even now relatively unavailable and will probably not be a significant alternative.

3. *Imposition of rationing according to the plan may induce increases in demand for unleaded, create shortages, and thus force misfueling; this may come about through (a) shifts*

in vehicle usage patterns, with more use of high mpg unleaded vehicles, and (b) through current provisions for gasohol. The first point is less certain than the second, as uncertain relative elasticities of auto and truck usage are involved, as well as uncertainties in the behavioral aspects. The second point involves the plan's exemption of ethanol (ethyl alcohol) from rationing; as long as supplies last, purchasers would be able to purchase 10 gallons of gasohol with ration rights for 9 gallons. Both leaded and unleaded users would do so, depleting unleaded supplies and forcing misfueling. The misfueling effect grows larger as ethanol supplies increase. *Exemption of ethanol from rationing is deemed to be ill-advised.*

4. *The significance to air quality of shortage-induced misfueling depends on duration and magnitude of shortages (and of price controls), on catalyst regeneration characteristics (which are poorly quantified), on public perceptions, and on government policies.* Duration and magnitude of the shortage may determine the number of catalysts exposed to lead, but not the extent of damage; available data indicate substantial (but not total) regeneration *if* proper fuel usage follows misfueling. Should motorists *believe* their catalysts to be destroyed by a single misfueling, or should they fear forced replacement by rigorous inspection and maintenance (I&M) programs, shortage-forced misfueling would tend to become repetitive misfueling, resulting (for those motorists) in near-total and permanent catalyst deactivation. *More data on the effects of lead and on the regeneration characteristics of the different types of catalysts (and emission-control systems) are needed; also, the possibility that overly-zealous I&M procedures could have adverse air quality effects under shortage conditions should be recognized.*

5. *The old-car issue is deemed to be of little real consequence if rationing exists for moderate periods (e.g., 9 months as assumed in the plan);* it could become significant if

rationing exists for long periods or if abuse (large numbers of cars per driver) leads to perceived inequities and lack of public acceptance. During rationing, any registered car would provide a source of income if its associated ration rights were marketed; a build-up in the population of old vehicles would thus be expected. The mere existence of these old, probably high-emission cars, is not desirable from an emissions standpoint, as they would probably receive some use; but their numbers are limited, and their generally poor gasoline mileage would insure that usage would be minimal. Some at-home misfueling (transfer of leaded from the tanks to unleaded cars) would probably occur due to the presence of these cars; there should, however, be *less* pressure to misfuel at home with rationing in effect than without rationing in effect, as gasoline of the proper grade would be purchasable directly for the car of choice.

6. *Bifurcated rationing, in which rights to purchase unleaded gasoline are distinguished from rights to purchase leaded gasoline, has been proposed as a means to minimize misfueling.* Two such schemes are considered here: in the first, coupons would be marked either "unleaded" or "leaded" and distributed appropriately; in the second, coupons would be marked either "unleaded" or "unrestricted", with "unrestricted" coupons going to "leaded" car owners. The second scheme appears to be preferable to the first from a misfueling standpoint and should reduce misfueling relative to the current undifferentiated plan, but no estimate of the magnitude of this reduction has been made. *More detailed analysis of costs and benefits under various hypothesized circumstances would be necessary before a recommendation for or against bifurcation could be made.*

7. *Many other issues may arise during rationing; the response of society under the presumed emergency conditions is by*

no means fully predictable. Allocation and priority procedures, which amplify shortages to the average motorist, will create resentment, and must be carefully considered. Counterfeiting or theft of coupons, theft for personal use or resale, etc. may all become significant. Much depends on the public's perception of the need for rationing and of the plan's equity.

8. *The general recommendation arising from the foregoing is that much detailed planning is needed regarding the fractional demand for and supply of unleaded and leaded gasoline and required octane levels, under shortage conditions both with and without rationing in effect. The complexities involved are substantial, involving conditions and procedures for which no experience is available. The investment involved in the catalyst systems is large; their rather fragile nature demands that the unleaded/leaded issue remain near the center of emergency planning considerations.*

1.0 INTRODUCTION

1.1 BACKGROUND

1.1.1 General

Catalytic converters have been installed in most of the automobiles manufactured in the United States since 1975 and represent a multibillion dollar investment. These catalysts are designed for use only with unleaded gasoline; if leaded gasoline is used--a practice known as misfueling--the catalysts are rapidly degraded in effectiveness and emissions of air-polluting species increase dramatically. The entire investment and approach to cleaner air thus hinges on the availability and use of unleaded fuel in catalyst-equipped cars; clearly, any development which affects the willingness or ability of the motoring public to use the proper fuel is a matter of national concern.

IDA has pursued questions related to misfueling since the spring of 1979, under EPA sponsorship,* with two papers having been prepared (Ref. 1, 2). This prior work, as well as work elsewhere, showed the potentially serious impact of shortages of unleaded gasoline, assuming leaded to be available, for inducing misfueling. The manner in which shortages are to be managed is thus of obvious concern to EPA. The Administration's rationing plan is such a management procedure, one designed for use should shortages of gasoline reach or exceed 20 percent, which is a considerably more severe situation than any encountered to date in the United States. IDA was thus asked, in connection with its studies on the effects of shortages of unleaded

*Contract 68-01-5150.

gasoline, to examine the proposed rationing plan for possible adverse consequences. This paper is the result of that examination.

1.1.2 The Standby Gasoline Rationing Plan

In accordance with Congressional mandate* the Carter Administration (DOE/ERA) in December 1979 proposed a Standby Gasoline Rationing Plan (Ref. 3). The proposed plan is similar in concept but differs in detail from a plan submitted earlier (Ref. 4, 5), which was rejected by Congress and withdrawn on September 27, 1979. Hearings were held on the proposed plan on January 7-8, 1980, and modifications have been introduced as a result: these modifications involved no major changes in the basic concept of the plan. The revised plan (Ref. 6, 7) was submitted to Congress on June 12, 1980 and passed (i.e., not rejected) as of July 30, 1980. The discussion here was developed largely on the version published December 10, 1979, but the revised plan has been reviewed for consistency with this treatment.

The Standby Gasoline Rationing Plan is a "white market" plan, which distributes rights (checks and coupons) to gasoline on the basis of vehicle registrations, and allows, through free sale or trade of such rights, for further distribution. The plan in detail is complex, through provision for priority rights to federal and state governments, and various other public and private groups. The plan is to operate in conjunction with an allocation plan, which distributes fuel by state. The rights distributions, "banking", and bookkeeping procedures are all necessarily quite involved. Costs for the rationing plan, once implemented, are estimated at $2 billion per year, to be recovered by a 2¢/gallon charge on gasoline. The plan does not extend to diesel fuel (at present).

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*Specifically, the Emergency Energy Conservation Act (EECA) of 1979 (Public Law 96-102) which amends the Energy Policy and Conservation Act (EPCA) (Public Law 94-163).

The Standby Gasoline Rationing Plan is to be worked out in detail in a pre-implementation study period, requiring at least a year and an estimated $103 million. The plan will then be in a standby phase, to be implemented, according to the law, when a 20 percent "shortage" of gasoline transpires, which requirement can be waived with Congress' permission. Once implementation is ordered, some time will be required (perhaps 90 days) to get rationing actually underway. The plan envisions rationing to last for a 9-month period.

The Standby Gasoline Rationing Plan is part of the overall set of plans being developed by the DoE to handle oil-shortage emergencies. The Standby Federal Emergency Energy Conservation Plan (Ref. 8) details numerous emergency procedures, other than rationing (speed limit enforcement, minimum purchases, odd-even rules, driveless days, 4-day work week, etc.) which may be imposed under emergency conditions.

1.2 PRINCIPAL ENVIRONMENTAL CONCERNS

This paper considers possible adverse effects (and their avoidance) of the Standby Gasoline Rationing Plan on mobile-source emissions, both prior to and during the plan's implementation, which would occur under rather severe shortage conditions. The principal concern is that, in the presence of the accompanying shortages, the plan may in some way induce misfueling. As noted earlier, such a procedure degrades and can destroy catalytic converters and increases mobile-source emissions. This work thus focuses on misfueling, a problem that was not treated in the "Draft Environmental Assessment" of the "Proposed Standby Gasoline Rationing Plan" prepared by DoE/ERA and published in June 1978 (Ref. 9). Furthermore, this work is intended to be of operational utility, i.e., it is assumed that rationing will be imposed under conditions called for by the plan; the theoretical question, as treated in Ref. 9, of the differences in environmental impact between rationing and no rationing under the same shortage conditions, is not addressed.

Misfueling by station attendants is illegal, and by virtue of restrictors in intakes, which must be removed or defeated (perhaps by a funnel), involves some difficulty for the individual. Misfueling, which usually takes place at self-service outlets, nevertheless occurs, and for a variety of reasons, as discussed in Refs. 1 and 2; these reasons include (1) price differentials (3 to 10¢ per gallon) between unleaded and leaded gasoline, (2) performance (leaded gasolines of a given grade are often two octane units better than unleaded gasolines), and (3) of most interest here, under shortage conditions, unavailability of unleaded gasolines should leaded be available. A recent, unpublished estimate* quotes current misfueling rates at 8 to 10 percent, based on 32,000 observations. This rate is not in good agreement with rates quoted by Austin and Eichbauer (Ref. 10) (1.6 percent in California during 1979, based on 13,371 observations) for reasons which are not yet clear; however, Austin and Eichbauer do point out the much higher misfueling rate (16.8 percent) when unleaded fuel was "unavailable",** so that there is no disagreement that shortages of unleaded gasoline can force misfueling, if leaded is available. Furthermore, as will be discussed here, and as pointed out in Dacy et al. (Ref. 1) and by Heinsheimer et al. (Ref. 11), random misfueling, which may result from shortages, leads to cumulative degradation with time of the catalyst population. Random misfueling may then be a more serious proposition in the long term than repetitive misfueling, which is normally for price or performance reasons and indulged in by a small subset of the population.

1.3 APPROACH

The approach used is first to postulate, in a general discussion, what adverse responses consumers may make to the rationing plan in its broadest sense, which here includes responses to

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*Nussbaum, B., EPA, private communication, May 19, 1980.

**Presumably, this meant that unleaded fuel was unavailable only at some stations. True unavailability would force 100 percent misfueling by unleaded cars.

discussions about rationing, to pre-implementation study periods, to emergency procedures instituted while rationing procedures are being put into effect, and to rationing itself, all in the presence of foreseen, feared, or real shortages. Selected issues, some of which are specifically related to the rationing plan itself, others to shortages, and still others somewhat commingled, are then discussed in some detail. A detailed modeling treatment of the shortage-induced problem is appended.

Note that it is assumed in this paper that self-service stations, at which most misfueling is believed to occur, would remain open during rationing. Such stations (in fact, all stations) would probably require that the right to purchase gasoline be established prior to its purchase, but this could readily be accomplished. (Many self-service stations now demand payment before the gasoline is delivered; addition of a coupon requirement would be trivial.) Actually, even full-service outlets might at times be forced to permit misfueling under extreme shortage conditions, so it is not clear that this assumption markedly affects the conclusions. Misfueling can, of course, as discussed herein, take place at home (by transfer of fuel) as well as at the pump.

1.4 OBJECTIVES

The objectives of this paper are to consider possible adverse effects of the rationing plan as it may develop and be implemented in the presence of shortages, and hopefully thereby, through appropriate, probably administrative, changes, to prevent such adverse effects from occurring. The broad outline of the rationing plan is taken as being fixed, as is its imposition should shortages of appropriate magnitude be encountered.

2.0 EXPECTED OR POTENTIAL EFFECTS: SELECTION OF ISSUES

2.1 INTRODUCTION

This section discusses the various possible effects which may occur prior to and during rationing. It should be recognized that public response and behavior during crises are difficult or impossible to predict.

The treatment in this section is entirely expository, aimed at selecting issues for further examination and at giving some impression of the severity of effects should shortages occur of such magnitude as to trigger rationing. The selected issues are treated in Section 3.0.

2.2 ON "SHORTAGES", CONTROLS, AND GASOLINE GRADES

Unless the requirement is waived by Congress, rationing is to be imposed only in the event of a 20 percent gasoline shortage. The term "shortage" is, to some degree, a matter of definition; normally it implies a reduction in anticipated supply over some period that is below the expected demand over that period *at some existing price level*. A plausible scenario is thus one in which some precipitous event occurs, cutting off that fraction of imported crude supplies which would lead to a 20 percent* reduction in gasoline supplies; an estimated 15 percent loss in total crude supply would be required. Rationing would then be ordered to avoid the expected large increase in gasoline price needed to reduce demand by 20 percent; some 90

*A 20 percent gasoline shortage would result due to priority allocation procedures in a 30 percent shortage to the average motorist. An expected allotment would then be 42 gallons per month per car.

days would be required for rationing to become operational. The rationing scenario thus implies the existence of or imposition of price controls. Price controls can be of various forms; presumably, there would be little or no control possible on the price of imports, but domestic controls could be imposed. The duration of rationing will likely depend on the form of these controls. Thus, the United States in summer 1980 used considerably less gasoline than it did in 1979; yet there was a "shortage" in 1979 and a "surplus" in 1980; a big difference, of course, was price.

Other controls, existing or newly imposed, would likely be in effect at the time of rationing. These would apply to average lead content, octane numbers, and the split between leaded and unleaded gasoline. Under such conditions, adjustments could be ordered to account, for example, for anticipated changes in leaded/unleaded demand ratios, etc. Note, as above, and in much of the discussion which follows, reference is made to "unleaded" and "leaded" gasolines, without consideration of the various grades. This is common practice currently* but begs details, which may be important; a user of unleaded premium (92 octane)** unable to find his preferred grade might misfuel with leaded regular if that gasoline is 89 octane, or leaded premium at 94 octane (which is seldom available), rather than unleaded regular, if that grade is at 87 octane. Or, if prices are allowed to respond to demand in some fashion, a station operator with an unleaded grade in short supply might run that grade's price up substantially, and cause price-induced misfueling. What, in fact, will happen will depend on the regulations in force at the time of rationing, which are not now known. These issues will require further examination during detailed contingency planning; in general, however, they are, and can be, treated only briefly

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* See for example Ref. 12.

** Octanes quoted here are (Research + Motor)/2 or (R+M)/2, and also known as Antiknock Index (AKI).

here. Some comments are included in Section 3.0. In effect, discussion of shortage effects in terms of "leaded" and "unleaded" implies an assumption that price and octane controls are in effect so that price-induced and octane-induced misfueling do not increase during emergency conditions.

2.3 POSSIBLE EFFECTS CREATED BY THE RATIONING PLAN

2.3.1 Effects Created by Publicity*

Rationing has been discussed since the 1973-1974 oil embargo. Shortages have also been encountered since that time, particularly in the spring of 1979. Talk of rationing might thus be expected to increase fear of shortages and induce behavior on the part of some individuals to protect themselves. The features of the bill itself will be examined in great detail by various columnists and advisory services; such examination has in fact already taken place.**

The plan provides valuable gasoline rights based on automobile registrations, and recognizes that this will induce registration and/or nonretirement of old cars ("junkers" or "clunkers"); limitations are expected to be imposed on the number of cars per household and on the date before which such cars would have had to be registered to be entitled to ration rights. Registration or nonretirement of such cars could thus begin as the public becomes aware of details of the rationing

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*The rationing plan was submitted to Congress at a time (summer 1980) when gasoline supplies were ample. This situation, and perhaps summer doldrums, led to relatively little evident interest and apparently minimal impacts of the types described in this subsection.

**For example, an advertisement (undated) received in the mail by this author early in 1980 offers with a subscription a copy of a "special report on gasoline rationing strategies," along with other bonuses.

plan. Clearly, this would be a direct effect of the rationing plan itself and needs to be discussed in terms of its potential for adverse impact.*

A second impact might be conventional hoarding (or prudent building up of stocks, depending on the viewpoint) by industrial, commercial, agricultural, and private users. The Lundberg letter for September 26, 1980 (Ref. 13) quotes sources that indicated a "startling pattern of stockpiling by big industrial and institutional users" in spring of 1979, which contributed significantly to a drawdown of inventories considerably before the average motorist knew there was to be a problem. Mere discussion of rationing probably would not trigger such action again, partly (it is suspected) because such users since that time very likely maintain much higher inventories than previously. Private users might, however, be stimulated to a degree with installation by wealthy individuals (where zoning or lax law enforcement permits) of say 500-gallon storage tanks**; some storage by the less affluent of gasoline in the tanks of old cars and of gasoline in 5- and 10-gallon cans around the home may occur. There are, however, some strong disincentives to keeping gasoline at home. Gasoline is a difficult and dangerous material to store (other than in the tanks of automobiles), and degrades with time: if stored in old cars, it must be siphoned if it is to be used in a newer car.

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*Maintenance of registration of junk cars can be quite inexpensive in some states. In Texas, e.g., while a license is needed, cars need neither insurance nor inspection if they are not driven. (According to Professor Henry Steele, University of Houston)

**A recent (September 1980) advertisement in a community newspaper begins, "Diesel Fuel and Gasoline. Why Pay Service Station Prices? Install an underground diesel fuel storage tank at your home...."

Misfueling potential from gasoline hoarding comes from possible impact on supplies of unleaded fuel, and from eventual home misfueling. Those storing gasoline in large tanks at home would quite likely be wealthy enough to store unleaded fuel, so that the home misfueling effect should be small. Institutional users, as in the spring of 1979, could have significant effects on supplies, but the relative demand for leaded and unleaded is unclear. Subjectively, however, it is difficult to foresee that the number of home storage installations--at least those triggered merely by simple discussion of rationing--would be large enough to affect supplies significantly. The volume of gasoline that could be stored in topped-off automobile tanks at home can be fairly significant,* but this would probably be well divided among leaded and unleaded varieties of gasoline. Thus some drawdown in gasoline supplies could occur as rationing is discussed, but it is difficult to see why such drawdown would necessarily lead to misfueling.

The plan, which provides equal gasoline rights per registered vehicle (with different allotments for motorcycles or mopeds, etc.) independent of the vehicle's gasoline mileage, would also encourage purchase of cars offering high gasoline mileage. Since emissions regulations are on a per-mile basis, such cars produce more emissions per gallon; nevertheless, this part of the plan seems consistent with national (DOT) objectives and in the national interest. The plan would also encourage purchases of mopeds and motorcycles, emissions of which per gallon of fuel used are higher than for automobiles. An owner of an auto plus moped might use his auto allotment in his moped, thereby increasing total emissions; national mobility would, however, again be increased, presumably with economic advantages accruing.

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*Assuming 100 million cars top off with an extra 10 gallons per tank, 1 billion gallons would be withdrawn from inventory. This represents about 10 percent of the gasoline normally in storage, but only about 1 percent of annual demand.

Plans to ration diesel fuel lag those for gasoline. This fact will be clear to readers of the legislation, and an increase in demand for diesel cars, and for home storage (possibly masquerading as home heating oil), might be anticipated. It is not clear that any significant environmental effect would be involved. (Incidentally, it is also not clear that fuel for diesel autos would be available during rationing, recognizing probable priority demands by truckers and farmers.)

No further discussion will be given to diesel fuel.

2.3.2 Effects During the Pre-Implementation Period

DoE anticipates that pre-implementation planning for rationing will cost $103 million, and require at least a year. This activity would also generate some publicity, with results similar to those discussed above. The same issues are evident. Others may arise in the event of supply cutoffs in this period, possibly calling for emergency measures, as discussed below.

2.3.3 Effects During Standby Period

The rationing plan will continue in a standby period, and be of mere background interest if supplies meet demand, once the pre-implementation work is completed. If price controls are in effect, modest local shortages, compounded by allocation procedures (as is understood to have been the case in the summer of 1979*), could conceivably develop which would not trigger rationing. Emergency procedures might then be implemented; discussion of these plans follows.

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* Anecdotally, at least, a 5 percent overall shortage, following allocation procedures to certain private groups (farmers, truckers, watermen) resulted in local urban shortages of as much as 25 percent.

2.3.4 Effects Immediately Following the Triggering of Rationing. Emergency Procedures and Significance of a 20 Percent Shortage

As noted earlier, rationing will probably not be "triggered" unless some severe event occurs, creating a projected discontinuity in the rate of oil deliveries; some 90 days would be required to put the plan into operation. The public response would vary with the nature of the event; a war involving the United States would create a different response than would, say, a revolution in a distant supplying country. The overall effect would be one of an expectation of shortages and, it is hoped, popular support (which would seem to be necessary) for the imminent imposition of rationing.* Those same effects noted in Subsection 2.3.1 would now occur with much greater intensity.

Various emergency procedures would be necessary immediately. These would probably be of the type given in Table 2-1 (from Ref. 8) although most of these are for smaller (< 10 percent) shortages than those necessary to initiate the rationing plan. More drastic contingency plans, not shown in Table 2-1 or described in Ref. 8, may well exist, but have not, to this author's knowledge, been published.

Other measures not shown in Table 2-1 are directed towards saving of distillates, etc.

The point is made in Ref. 8 that the indicated savings are not additive. The figures are interesting primarily in terms of their magnitude. Even assuming additivity and using the maximum in each range, the total is only 1120 MBPD, versus a shortfall, at a 20 percent shortage, of about 1300 to 1400 MBPD.

*Professor J. Eugene Webb of Stanford University has commented on the critical importance of public acceptance to workability of the plan. He doubts that rationing could be imposed in the absence of national crisis, and would work only if the public viewed it as equitable. Many aspects of this point could be pursued further.

TABLE 2-1. FEDERAL STANDBY GASOLINE CONSERVATION MEASURES AND ESTIMATED SAVINGS*

MEASURE	DESCRIPTION	ESTIMATED REDUCTION IN GASOLINE DEMAND, MBPD**
Public information	Multimedia publicity about ways to cut fuel use	70-220
Minimum fuel purchase	-	Not available
Odd-even purchase	-	Not available
Employer-based commuting	Carpools, vanpools, parking restrictions, work at home, etc.	55
Speed limit	Enforce 55 (or 45) mph limit	30-400
Compressed work week	e.g., four 10-hour days	300
Vehicle use sticker	Forego vehicle use 1-3 days per week	10-60
Watercraft restrictions	Forego weekend boat use, 1-2 days per week	35-85

*From Ref. 8.

**Thousands of barrels per day.

Quite obviously, an abruptly-imposed 20 percent shortage would involve serious disruptions; unfortunately, 20 percent is by no means a limiting case. A Persian Gulf closure, for example, would result in a loss to the United States of about 6 MMBPD (Ref. 13), which corresponds to a crude loss of the order of 30-35 percent, with greater gasoline loss. An "OPEC embargo", as defined in Ref. 14,* would lead to a loss of about 4 MMBPD.

The 90-day period prior to initiation of rationing may well be a critical one in terms of misfueling; plans for this period,

*Direct U.S. imports through the Persian Gulf or from OPEC are much smaller than these figures. The extra loss is due to diversion to Europe of U.S. imports under the International Energy Program agreement. (See Ref. 14.)

once developed, may need examination for misfueling aspects. The following classes of events, in addition to those noted earlier (clunker nonretirement, hoarding, etc.) might be expected, varying with the measures imposed:

1. Hoarding by industrial, agricultural, commercial and private users.
2. Long lines at gasoline stations.
3. Preferential filling of cars with large gas tanks (unless maximum purchase rule is imposed) and of cars with maximum cruise range.
4. Theft of gasoline (from autos and of tank trucks), with little concern for leaded/unleaded niceties, and some misfueling.
5. Random at-pump misfueling, where motorists in line find unleaded fuel exhausted before leaded fuel.
6. At-home misfueling, as motorists transfer gasoline from low mpg to high mpg cars.
7. Possible unanticipated increases in unleaded demand fraction (as old, poor-mpg cars are given little use) with shortages in unleaded, and forced misfueling.

A number of these effects will probably be ameliorated once rationing is in effect. The period involved in this phase (up to 90 days) is significant, however, and since, in a sense, this period can be considered part of the plan, the effects of shortages without rationing merit consideration for misfueling potential.

2.3.5 Effects During Rationing

The arrival of formal rationing should lead to a more orderly marketing situation, drivers having at least some confidence in their ability to get the allotted quantities of gasoline in

any given period.* Very few registered vehicles would be retired once rationing begins, even if existing only as scrap heaps following collisions. As noted heretofore, many other effects would also enter, and some effects would be eased. In addition, new effects, such as counterfeiting and various forms of fraud, would enter.

Other problems, created by the specific procedures implemented could also enter; one such, which is easily recognized, is the treatment of gasohol, a blend of 10 percent ethanol and 90 percent unleaded gasoline. The plan proposes that the gasoline portion of this mixture be the only portion rationed; i.e., coupons for 90 gallons of gasoline would permit purchase of 100 gallons of gasohol. The effects of this provision will be discussed at length.

Allocation procedures, which provide priority users with gasoline ahead of non-priority users, "amplify" shortages. A 20 percent shortage of gasoline, as noted earlier, results in a 30 percent shortage to the average motorist. Larger shortages would be even more serious. It is highly probable that these policies would be heavily resented by non-priority users. The point is important in terms of public acceptability and might have indirect, but unquantifiable, effects on misfueling; it is given brief discussion in Section 3.0.

A related issue is the oft-suggested procedure in which unleaded and leaded gasoline are rationed with so-identified coupons. This is the so-called bifurcated rationing scheme, and merits some discussion.

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*To quote John Kenneth Galbraith (Ref. 15), "the purpose of rationing is to give the person who has the ration coupon the security that he can go to the pump and get gasoline without waiting. It's an absolute disaster if, when he goes, he finds it's empty." He points out that Sunday driving was banned in some cases in World War II to avoid this.

2.4 RECAP OF ISSUES

The foregoing "scenarios" approach obviously commingles problems associated with rationing and with shortages. While problems associated with both shortages and rationing are of interest, it is well to distinguish between them where possible.

The issues selected from the foregoing discussion which appear to merit further treatment follow:

- Shortage-related issues (with or without rationing)
  - At-pump misfueling (shortage-induced) and its avoidance
  - At-home misfueling
  - Gasoline theft
- Ration-plan specific (or implementation) issues
  - Effects on supplies
  - Clunkers, direct or induced effects
  - Gasohol policies
- Related issues
  - Allocation aspects
  - Bifurcated rationing
  - Regenerability of catalysts
  - I&M aspects

Note that hoarding is not specifically included in the list. Its potential importance to misfueling seems to be unquantifiable. Based on past experience, however, some controls on large-scale users might well be necessary to prevent rapid drawdown of supplies. Note also that coupon theft, counterfeiting, etc., are not included. These could be serious problems during rationing, but no treatment of their potential effect on misfueling suggests itself and no further treatment is included.

3.0 REVIEW OF SELECTED ISSUES

3.1 SHORTAGE-RELATED ISSUES

3.1.1 At-Pump Misfueling (Shortage-Induced) and Its Avoidance*

A shortage of gasoline does not by itself lead to misfueling and adverse air quality effects. In fact, a reduction in fuel usage should reduce total emissions and improve air quality. This is the argument advanced in the DoE Draft Environmental Assessment (Ref. 9), wherein total emissions by region with and without rationing are reported. The difficulty comes, as noted heretofore, when through chance or through errors in forecasting or in distribution, unleaded becomes in short supply relative to leaded, so that unleaded cars are forced to use leaded fuel for simple availability reasons; the converse situation, wherein leaded is in short supply and leaded cars are periodically or randomly forced to use unleaded, has no corresponding effect. Theoretically, random misfueling has cumulative effects on the catalyst population, as will be discussed later. If follows therefore in a rather obvious way, that under overall shortage conditions, a *relative* deficit of leaded gasoline should be maintained, so that fuel exhausted first is more likely to be leaded than unleaded.

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*Note that this discussion applies in concept, whether or not rationing is in effect. If rationing results in orderly distribution of supplies, the coupon holder would feel little pressure to misfuel if a specific station were to have leaded but no unleaded. If, however, supplies and coupons are in tenuous balance, so that unleaded disappears from a given urban area (for example towards the end of a ration period) then misfueling could be forced.

Before proceeding, it should again be noted (as in Section 2.2) that the discussion above and in much of what follows treats leaded and unleaded gasolines as entities, ignoring the splits between premium and regular grades. As was stated, this is common practice, the general implication being that octane levels and splits between grades are known, specified, or simply a refiner's problem to meet demand. To what extent this treatment will be valid under the emergency conditions and regulations under which rationing will exist is difficult to say. Ideally, the pre-shortage unleaded premium fraction should be maintained during shortages. Also, ideally, unleaded and leaded regular should both be the same octane. Currently, leaded regular is 89 octane, and unleaded regular must be at least 87 octane, but some refiners market 89 octane. Unleaded supplies can be increased by decreasing octane, as discussed below, but adverse side effects (octane-induced misfueling) may accrue which would be undesirable. In effect, lumping of grades together as unleaded or leaded gasoline is equivalent to assuming that the octane issue is secondary and will be under control during emergency conditions. This is not a trivial assumption; clearly, further examination of this issue will be needed during pre-implementation study periods. Certain effects on refining capacity are included in this section.

Granted that a need exists to maintain a relative deficit of leaded fuel under shortage conditions, the question of degree of deficit needed is of interest. For this purpose, a mathematical model has been developed, which is included in Appendix A to this report. The model, which probably provides an upper bound to shortage-induced misfueling rates is a probabilistic one, in which drivers and station operators behave mechanistically, pumping preset ratios and quantities of leaded and unleaded fuel to randomly arriving drivers; those stations which happen to serve a disproportionate number of unleaded cars do so by misfueling the excess. The model is not intended

to predict actual behavior; however, it does provide quantitative indication of the advantages of maintaining a deficit in leaded for various demand ratios, as the unleaded portion of the fleet grows. In general, a relatively small deficit in leaded (probably, at most, 5 percent in leaded, with an equivalent amount of additional unleaded*) should be sufficient to insure with high probability that leaded gasoline would disappear first and shortage-induced misfueling would be very small.**

The contention that relative surpluses of unleaded and relative deficits of leaded should be maintained under all conditions when shortages are present is held throughout the remaining discussion. Conversely, it is argued that any policy which more or less suddenly increases the demand for unleaded, when supply ratios are more or less fixed, can lead to shortages of unleaded and to forced misfueling.

The question immediately arises whether forced relative surpluses of unleaded can be established and maintained. This question cannot be answered for the indefinite future nor as a function of the degree of crude shortage, but some observations and data are available which suggest at least the *physical* feasibility of doing so. Political feasibility, as discussed briefly below, may be another matter.

The most direct evidence, which for physical feasibility relates only to current demand ratios is that, as of February 1980, the stocks of unleaded gasoline were building faster than were the stocks of leaded (Ref. 12); both the absolute sales of

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* To illustrate the terms used here, if the theoretical demand ratio is for 40 leaded to 60 unleaded, a "5 percent deficit" of leaded means the ratio delivered is 38 to 62.

** It is recognized that this policy will impose costs on both leaded and unleaded gasoline consumers. The surplus should obviously be kept to a minimum consistent with uncertainties in demand and with misfueling prevention. The deficit should be reduced as demand and misfueling behavior data permit.

unleaded gasoline and the percentage of unleaded were below projections. Reference 12 ascribes this surplus to EPA concerns in October 1979 about a shortage of unleaded: at that time EPA waived a lead phasedown rule for refiners producing 45 percent of their total gasoline output as unleaded or if they increased their production by 6 percent over the same year's earlier quarter. Percentage sales of unleaded as of February 1980 were in the 41 percent range, several points below forecast percentages. The question of why this occurred is being pursued in a separate study at IDA,* also under EPA sponsorship.

The question of projected unleaded production capability has been treated in depth by the National Petroleum Council (NPC) (Ref. 16), for the period through 1982, always assuming adequate crude.

The National Petroleum Council study, which was carried out by survey techniques in 1979, summed up refinery industry projections as to equipment expected to be in place at certain times, but the oil situation changed rapidly during 1979 so that there is no guarantee that all the projected installations included in the surveys will be (or have been) carried through. Nevertheless, the data are of considerable interest and should be reasonably accurate for the 1980 and prior periods. Data from the report are given in Table 3-1.

According to Ref. 16, the average octane number of unleaded gasoline in 1978 was 88.5 AKI $\left(\frac{R + M}{2}\right)$. According to Table 3-1, the unleaded capacity in 1980 (apparently as of January 1, 1980, judging from the context in Ref. 16) was to be 4.335 MMB/D at 88.85 AKI, with a total capacity of 7.514 MMB/D. The projected demand for 1980 is quoted as 7.58 MMB/D total, with 48.2 percent, or 3.65 MMB/D as unleaded. By contrast, recent (February 1980) demand for unleaded gasoline was about 2.77 MMB/D, based on 41 percent of a total demand of 6.75 MMB/D (Ref. 12). These

*Thomas, R. William and Mark S. Carey, "U.S. Gasoline Demand: Will the Decline Continue?", in preparation.

TABLE 3-1. U.S. NATIONAL REFINING CAPACITIES
(Motor Gasoline, All Grades. Various Options.)
Source: Ref. 16

Year	Refinery Runs	Unleaded[a] AKI Max'd	Unleaded[a] AKI Avg	Unleaded[a] MB/D	Leaded[a] MB/D	Total MB/D	Pool Lead,[a] gpg[a]	Percent Unleaded
1978	16,029[b]	-	88.50	-	-	7237[b]	-	c
		87	87.00	4615	2650	7265	0.8	
		89	88.82	3515	3715	7230	1.1	
		90	89.65	2973	4240	7213	1.3	
1980	17,182[b]	-	-	-		7588[b]		
						7580[d]		48.2[d]
		87	87.00	5927	1679	7606	0.3	
		89	88.85	4335	3179	7514	0.5	
		90	89.65	3458	4024	7482	0.5	
1982	17,984	-	-	-		7846[b]		
						7550[d]		60.0[d]
		87	87.00	6484	1405	7889	0.3	
		89	88.85	4936	2861	7787	0.5	
		90	89.66	4125	3627	7752	0.5	

a. Theoretical capacities under alternative goals based on equipment in place or projected (Tables 23 and 25, Ref. 16).

b. Actual or projected (see Table 17, Ref. 16). Crude oil plus condensate plus other feed stocks.

c. 1978 figures not given. 1977 figures (Fig. 24, Ref. 16) quoted as 7.18 MMB/D, 26.6% (1.91 MMB/D) unleaded, 73.4% (5.27 MMB/D) leaded.

d. Figure 24, Ref. 16.

figures should probably be seasonally adjusted, but nevertheless indicate both that a reduction in total demand for gasoline has occurred since the NPC projections were made and that a considerably lower fraction of this demand is for unleaded gasoline. The current apparent surplus of unleaded is thus consistent with an *overcapacity* situation.

The 1982 capacity shown in Table 3-1 at 88.85 AKI is 4.936 MMB/D out of 7.787 total, or 63 percent unleaded, versus 60 percent of 7.55 MMB/D or 4.53 MMB/D unleaded quoted as expected demand. If it is noted that the unleaded capacity figure quoted for 1980 in Table 3-1 is 4.335 MMB/D, and it is assumed that this figure represents equipment now in place, then the figure of 4.53 MMB/D quoted as demand in 1982 would seem to be almost within reach; or if actual demand is appreciably below projected demand, as currently is being experienced, then capacity in place now should fill 1982 requirements. Furthermore, using Ref. 16 (Fig. 24), the 1985 demand for unleaded is 5190 MB/D, 72.5% or a 7160 MB/D total, and thus in the ranges quoted at 87 and 89 AKI for 1980 and 1982. The principal question, aside from crude supply, is one of octane requirement. The rapid decline in capacity with increasing octane is worrisome since octane requirements for new cars may be creeping upward (Ref. 17), as shown in Table 3-2, and cars tend to require increasing octane as they age.

TABLE 3-2. OCTANE REQUIREMENTS FOR NEW CARS
(Ref. 17)

Model Year	% Satisfied At 87 AKI	Octane Required to Satisfy 90%
1975	82	88.5
1976	75	89.9
1977	75	88.7
1978	73	89.4
1979	71	89.4

Read from bargraph.

Note that the unleaded supply situation has changed drastically since the spring and summer of 1979. At that time, shortages of gasoline (primarily of unleaded gasoline) were forecast and encountered. The unleaded supply problem was due to a combination of a shortage of crude oil and a claimed lack of adequate reforming and other facilities (and to a lack of incentives) to make unleaded gasoline. To alleviate the situation, President Carter announced in April 1979 a suspension of the ban on use of MMT* in unleaded gasoline and a relaxation of phasedown rules for tetraethyl lead in gasoline. These combined actions were expected to permit an increase in both total gasoline (by a small amount) and a substantial (340,000 BPD) increase in unleaded, at the expense of leaded. (In effect, the higher octane constituent of the pool intended for leaded gasoline was to be transferred to unleaded and, as necessary, upgraded with MMT; the octane of the remaining material was to be increased as necessary by use of additional lead.) As it worked out, less MMT was used than anticipated, with a shift from leaded pool during summer 1979 of only about 130,000 BPD (which figure itself may be an overestimate**), and the ban on use of MMT was reinstated as of October 1, 1979.

The above data suggest that, unless octane requirements increase significantly in the next several years (or unless crude quantity changes are in some way limiting†), then unleaded gasoline refining *capacity* should be available to exceed the nominal unleaded demand, at least in national average terms. (Local

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*A manganese-containing octane-improving additive which has been used (until September 1978) in unleaded gasoline (see Ref. 1).

**Memorandum to the Administrator from Joan L. Bernstein (undated; *ca* October 1979).

†No data have been seen during this study which indicates how changes in crude supply (total or in terms of sulfur content) would affect the producibility of unleaded gasoline. Superficially if, say, reforming capacity limits unleaded production, a decline in total throughput should permit a higher percentage output of unleaded.

situations may differ from national averages.) However, refining capacity, as suggested earlier, may not be the issue of greatest importance. Very likely, shortages of gasoline would once again lead to pressures of the type experienced in 1979. Production of unleaded gasoline reduces the yield of gasoline obtainable from crude oil; the magnitude of the loss depends on the types of refining equipment available, so that the achievable surplus of unleaded gasoline in severe shortage conditions remains an open question. A possible argument in defense of such a policy is advanced in Section 3.2.1 below.

3.1.2 At-Home Misfueling

At-home misfueling, in which stored leaded gasoline is used in a car calling for unleaded gasoline, would come about on occasions when leaded gasoline is available and unleaded is difficult or expensive to obtain. Many homeowners store leaded gasoline, usually for lawnmowers; many others have more than one automobile, one of which uses leaded gasoline and gets poorer mileage than the other.* The desire to get the most miles from available gasoline would seem to provide a powerful incentive to misfuel, increasing as the shortage persists, or as a ration period nears an end. The deterrents would be the fear of "damaging" the newer car or of being forced to replace an expensive catalyst.

Some crude appreciation of the *potential* for misfueling by transfer of fuel from old to new cars can be achieved by noting that 63 percent of automobiles are owned by households having two or more cars (Ref. 18), and that by 1981, about 22 percent of the automotive fleet will be 1974 models or older (Ref. 18), all of which use leaded gasoline, and many of which get poor

*Unleaded gasoline could be purchased and put in the tank of the poor-mileage car for storage. Such gasoline would--at least with the first tankful--almost certainly be contaminated with lead due to initial leaded gasoline still in the tank.

mileage (although pressure to keep only the better-mileage versions is obvious). Many cars and light trucks built since 1974 use leaded gasoline, but many of these (imports primarily) get fairly good mileage. Misfueling potential exists in that fraction of households having two or more cars*, one of which gets poorer mileage than the other and uses leaded gasoline. From the general scale of the numbers quoted above, a guess is that some 25 to 50 percent of the unleaded fleet might be subject to at-home misfueling by transfer from an old to a new car. How much more potential should be added for use of lawnmower gasoline, stored in 5-gallon cans, for example, is unknown.

The pressure to misfuel at home is clearly a maximum when it is very difficult to get gasoline at a time and of the type desired. In the absence of rationing, and in the presence of shortages, so that long lines occur, the pressure would be to fill the car with the largest gas tank; this car might well use leaded gasoline. In the presence of rationing, the incentive to do so would seem to be minimal; one could at least get gasoline of the type desired, in preset quantity, at the times desired. Various ramifications are possible (an entrepeneur/hoarder might decide to fill all his tanks at the beginning of a ration period, in fear of later unavailability) and use or sell the gasoline thereafter. However, rationing, or any approach to an orderly market would seem to minimize the at-home misfueling problem. Nevertheless, the potential is present, and appears to be significant.

Another form of at-home misfueling is discussed in Section 3.2.2.

3.1.3 Theft

Shortages of gasoline are inevitably associated with increased theft, most commonly of the small-scale siphoning variety, but also including thefts of tank-truck quantities,

*Conceivably, transfers between households could also take place (even without theft).

pipe-line taps, and even oil-tanker highjacking on the high seas. From a misfueling standpoint, the small-scale theft problem is probably the most serious, although data are not at hand; the larger-scale thefts, unless mislabeling occurs for price reasons (which is possible), would probably affect fewer vehicles.*

The number of cases per year of siphoning, and the care with which thieves might choose gasoline of the proper grade is unknown; the number of such incidents may well be in the millions of cases per year. Certainly the fear is widespread, judging by the quick sell-out of locking gas caps during recent shortages.

Theft is largely a matter of shortage. It could be a significant aspect in misfueling, but rationing's effect thereon is difficult to predict.

3.2 ISSUES ASSOCIATED WITH RATIONING

3.2.1 Direct Effects on Unleaded Supplies

Imposition of rationing following a period of some disruption (see Section 2.4) should lead to a more orderly marketing situation. However, imposition of rationing would inevitably change the behavior patterns of the motoring public. Ignoring the white-market aspect, and thus overstating the case somewhat, the problem in the absence of rationing is to find and buy as much gasoline as possible. In the presence of rationing, however, the problem is to drive as many miles as possible within one's allotment.** The at-home misfueling problem would again

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* Gasoline tank-truck highjacking, (Ref. 20), has generally not been profitable enough for organized crime to be significantly interested; cargoes worth $100,000 or more are preferred. However, as the price of gasoline and ease of disposal both increase, the number of such thefts would also be expected to increase.

** This behavior is ascribed to the rationing plan because the plan is based on registered vehicles rather than on individual need: it is, of course, also a result of shortage.

arise, but, as pointed out earlier, should be alleviated by the presumed ability to buy gasoline of the type desired. The mileage maximization problem still arises, and the effect may well be to cause a significant change in demand for unleaded gasoline, since high mpg cars would be preferentially put to use. The effect is illustrated by the figures in Table 3-3.

TABLE 3-3. EFFECTS ON UNLEADED DEMAND OF RATIONING AND OF NON-USE ON LOW-MPG CARS (SWEENEY MODEL; 1982 FLEET, REF. 21)

Item	No Rationing	Rationing (Shortage)	
	Full Fleet	Full Fleet	Under-13-mpg Fleet Eliminated
Leaded	1786 MB/D 30%	1513 MB/D 32%	1325 MB/D 28%
Unleaded	4165 MB/D 70%	3187 MB/D 68%	3329 MB/D 72%
(Diesel)	(1050) MB/D	(959) MB/D	(984) MB/D
Total Gasoline	5951 MB/D 100%	4700 MB/D 100%	4654 MB/D 100%
Gasoline Price/gal	$1.57	$3.59	$2.90
Fleet mpg	17.34	17.06*	17.91

*Note that average mpg drops because the price elasticity for gasoline trucks is less than for autos; thus, relatively heavier use of low-mpg trucks occurs.

Table 3-3 is based on the Sweeney model.* The Sweeney model is a gasoline-demand model, in which responses to price changes are of prime interest. To use it in this case, in which a 20 percent reduction in gasoline was imposed, required assumption of a gasoline price. When the fleet was changed arbitrarily, for example, by eliminating low-mileage cars, the required price changed. The model was not developed for this use, but results

*The Sweeney model is in use at DoE in the Energy Information Administration. It is described in Ref. 21. These calculations were performed by Mark S. Carey of IDA, using a slightly modified Sweeney model (see footnote page 3-4).

(Table 3-3) are nevertheless believed to be of interest. Table 3-3 is based on a nominal 1982 case, in which (1) there is no shortage, with gasoline at $1.57/gal; (2) a shortage is met by a price rise (coupon plus pump price, or pump price alone) to $3.59/gal, reducing demand 21 percent (about 20 percent); and (3) the shortage is met by a combination of rationing and elimination of the low-mpg (under 13 mpg) fleet. Elimination of this low-mpg fleet component reduces fleet size, and a nominal 20 percent drop (actually 22 percent) in consumption is met with gasoline at $2.90/gal. The relative demands and the percentages for unleaded should be noted; the full fleet case (column 2) calls for 3187 MB/D of unleaded (68 percent, versus 70 percent prior to a shortage) whereas the fleet with low-mpg cars eliminated (column 3) calls for 3329 MB/D (72 percent) unleaded. The drop in percentage demand (from 70 to 68) for unleaded with the full fleet in use was a result of lower demand elasticities for trucks using leaded gasoline than for light-duty vehicles. The increase in demand for unleaded as low-mpg cars are eliminated is in the expected direction.

Further quantification of effects of rationing on the percentage of unleaded gasoline demand would seem to be highly desirable if shortages of unleaded are to be avoided during rationing. The effects would be smoothed over by similar pressures existing during the emergency period (90 days perhaps) when a shortage exists prior to formal rationing. Even in the absence of credible quantification, however, it appears that it may be desirable to move during rationing to *higher* fractions of unleaded than to *lower* fractions which public pressure would call for to increase total gasoline supplies, as discussed earlier. This policy, once further explored and quantified, might be defensible, not only on air quality grounds but also on the basis that the legal vehicle miles travelable (national mobility) would be increased by increased production of *unleaded gasoline*, even though maximum *gasoline* production is not

achieved thereby.* The optimum fraction would very likely vary with geographic region, with the degree of inhibition against misfueling, and with the prevalence of owners with both leaded and unleaded vehicles.

3.2.2 A Secondary Effect: Octane Questions in Mileage Maximization

Much of the discussion in this paper has ignored the octane issue. There is no question that octane enters into gasoline mileage. According to Ref. 22, cars which knock on regular unleaded gasoline can be retuned to prevent knock by adjusting the spark ignition timing, but at a loss in fuel economy, with each one degree in spark retard causing a loss of 1 percent in fuel economy--up to eight degrees of retard are sometimes used. Mechanically-inclined individuals who have been using 87 AKI unleaded, might, in seeking maximum mileage, shift to unleaded premium (typically 91.5 AKI), if available, and retune their cars. If the unleaded premium is unavailable, several options might suggest themselves, the first of which would be to switch to leaded premium (94 AKI) or to leaded regular (89 AKI). Leaded premium, already rare, would probably be unavailable. Also, some unleaded regular is now 89 AKI; if this material is available there would be no performance advantage in going to leaded regular. If only 87 AKI unleaded is available, there would be an advantage, so that from this standpoint elimination of this octane differential would be desirable.

Another possibility might present itself. This is the addition to the tank of octane-improving materials to the available unleaded. Conceivably, tetraethyl lead, plus the usual additives (ethylene dibromide), might be available for home addition. Manganese components might also be available, which would be less harmful to catalysts.

The quantitative significance of the foregoing is unclear, but, as noted earlier (Section 3.1.1), it is evident that octane

*I am indebted to Professor Alfred Blumstein of Carnegie-Mellon for this intriguing suggestion.

levels, as well as unleaded supply levels, must be kept as high as possible during periods when strong pressure exists to maximize mpg on available automobiles.

3.2.3 The Clunker (or Junker, or Old Car) Issue

The rationing plan distributes gasoline rights on the basis of vehicle registration. With a 20 percent shortage, which, as pointed out earlier, is by no means a limit, each car would receive ration rights for 42 gallons per month. The coupon value in the white market, assuming a 20 percent shortage, an elasticity of - 0.25, and an initial price (pre-shortage) of $1.50 per gallon, is estimated by DoE (Ref. 7, p. 4-9) to be $2.13 per gallon.* Under these circumstances, each registered car would be a valuable object, capable of returning to the holder some $1074 per year. How much such a car would be worth on the market is uncertain, since the risk would be great that rationing would be discontinued and the investment rendered valueless; however, it is doubted that any owner would casually retire such an income producer.

This aspect of the problem has been well aired publicly and cut-off dates and other procedures could be used to minimize the acquisition of such cars. The environmental aspects can be put in perspective by examining the limitations on the increase in such cars. The data in Fig. 3-1 and Table 3-4 are pertinent.

Note in Fig. 3-1 that sales and retirements normally parallel each other, with sales exceeding retirements by 4 or 5 million vehicles per year. Sales dropped in 1974 following the gasoline

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*The result is based on a constant-elasticity assumption, in which $P_M = P_p R^{1/E}$, where P_M is the market clearing price under reduced demand ratio R, for original pump price P_p. In the case cited, P_M is $3.66, P_p is $1.50, R = 0.8, and E = - 0.25. The theoretical coupon value of $2.16 is reduced by DoE to $2.13 to allow for 3¢ administrative expense.

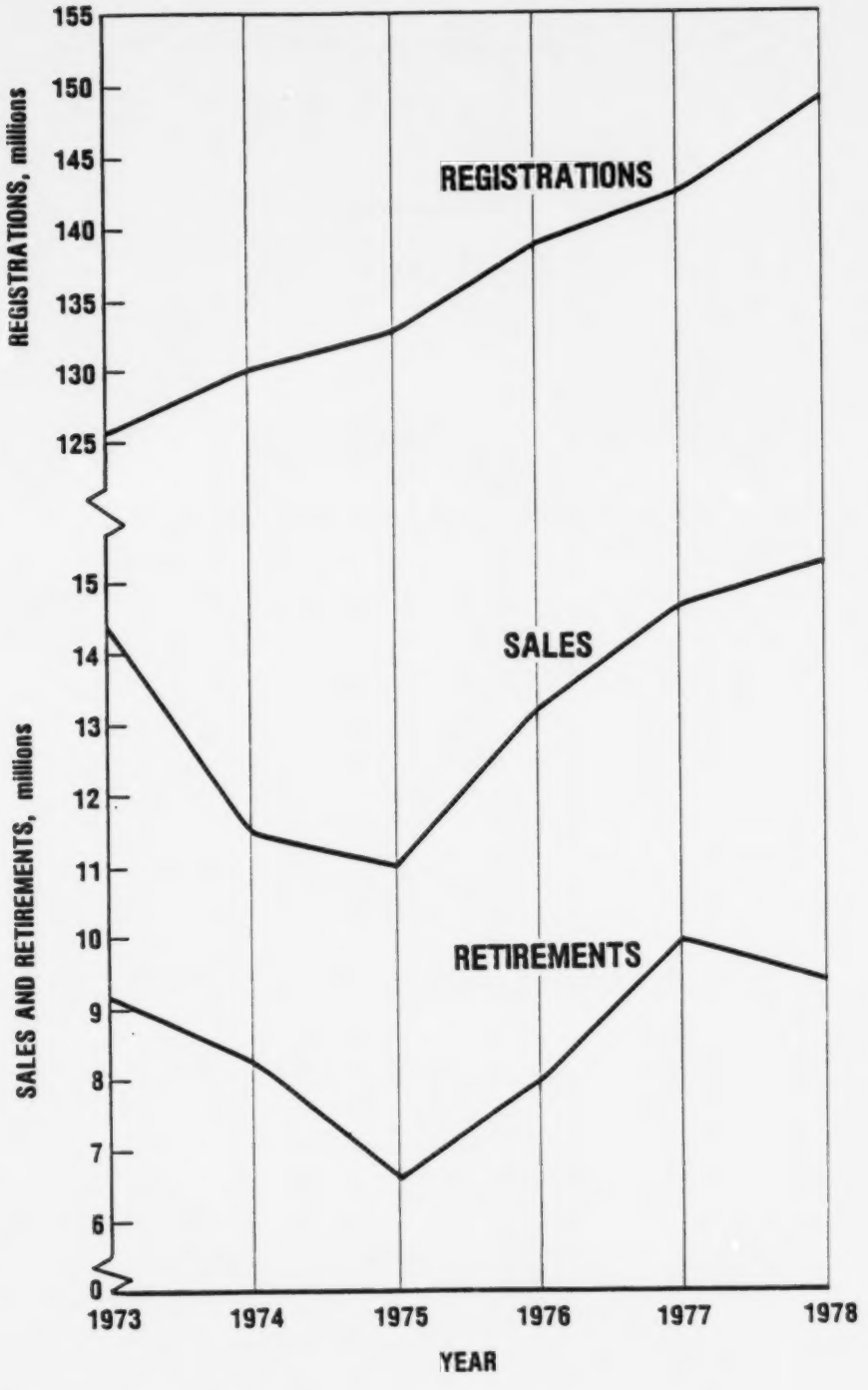

FIGURE 3-1. Registrations, sales, and retirements of cars, trucks, and buses in the U.S. 1973-1978. (Ref. 18)

TABLE 3-4. SALES AND RETIREMENTS OF VEHICLES, MILLIONS (Source: Ref. 18)

Year	Passenger Cars			Trucks and Buses			Total		
	Registrations	Sales	Retirements	Registrations	Sales	Retirements	Registrations	Sales	Retirements
1973	102.0	11.439	7.987	23.7	3.008	1.208	125.7	14.447	9.165
1974	104.8	8.867	7.194	25.1	2.587	1.047	129.9	11.454	8.241
1975	106.7	8.640	5.669	26.2	2.351	0.908	132.9	10.991	6.577
1976	110.4	10.110	6.829	28.2	3.044	1.097	138.6	13.154	7.926
1977	112.3	11.185	8.234	30.1	3.486	1.668	142.4	14.671	9.902
1978	117.1	11.312	7.907	31.9	3.914	1.426	149.0	15.0226	9.333

crisis in the 1973-1974 winter, but bottomed out in 1975, presumably due to the recession's end. Of course, gasoline rationing was not imminent in this period.

The absolute number of vehicles reaching retirement age is evidently 6 to 10 million per year, with some flexibility evident in the decision. Note that even if all retirement-age vehicles were kept in service rather than retired for a period of, say, 1 year, the number of registered vehicles would increase on the order of 5 percent. Most of these vehicles would receive rather little use, so that the gasoline demand would be affected considerably less, perhaps 1 to 2 percent, and probably weighted towards leaded gasoline (pre-1975). To the extent that these little-used cars would be filled with leaded, the leaded gasoline demand would be increased, mitigating the effect noted earlier on unleaded supplies. (Note that many of the non-retired vehicles would be owned by affluent individuals as third or fourth cars.)

Some crude numbers can be put on "clunker effects." Table 3-4 indicates sales of autos are normally of the order of 10 million per year, and of trucks and buses, roughly 3-1/2 million per year. Retirements of autos are on the order of 7 million per year and of trucks and buses 1-1/2 million per year. With these numbers, crude estimates can be made of the populations of such vehicles, with and without rationing, assuming rationing begins in 1981. The figures are given in Table 3-5.

The figures in Table 3-5 are not intended to be read as a forecast, since the number of cars which would be sold under rationing is unknown. The trends illustrated, however, are believed to be in the right direction; the divergence between the rationing and no-rationing scenarios is in fact probably understated, since the number of gas guzzlers retired in the absence of rationing but in the presence of shortages would be greater than

TABLE 3-5. NOMINAL MOTOR VEHICLE REGISTRATIONS, IN MILLIONS
(Excluding Motorcycles)

Year	Business As Usual		With Rationing[a]		
	Passenger Cars	Trucks and Buses	Passenger Cars	Trucks and Buses[b]	Normalized Ration Rights Per Passenger Car[c]
1978	117	32	-	-	-
1979	120	34	-	-	-
1980	123	36	-	-	-
1981	126	38	126	38	1.00
1982	129	40	136	(41.5)	0.95
1983	132	42	146	(45)	0.90
1984	135	44	156	(48.5)	0.87
1985	138	46	166	(52)	0.83

a. Business otherwise as usual. Used as the proxy for a period with a shortage but without rationing.

b. The figures shown assume all such vehicles have fuel ration rights, discouraging their retirement. If diesel fuel is not rationed, the figures are obviously incorrect, hence the parentheses.

c. Constant total U.S. consumption. Based on passenger cars only.

normal and the number retired in the presence of rationing would be near zero. The number of new cars sold with rationing would probably also be larger than normal. At any rate, with rationing, the number of registered vehicles would increase more rapidly than normal with time, and, even if total gasoline consumption were held constant (it might well decrease) the ration rights per vehicle would drop. This decrease would be perceived as a decrease in the quality of life, and, if the causes are understood, might lead to increased social friction. But the effects would obviously be slow to build up.

The numbers in Table 3-5 are based on the assumption that rationing, once begun, would continue. This is contrary to the central DoE assumption, which is that rationing would be used to handle a crisis situation of some sort, and would probably be of modest duration (perhaps 9 months).

The environmental effects of the enhanced old car fleet are impossible to quantify, since usage of such cars would be minimized. The cars might need to be operable, if only to pass periodic inspections. As an illustration, if such cars are assumed to use 10 percent as much gasoline as the rest of the fleet, and if emissions (as hydrocarbon) are, say, 5 times those of the average fleet car, then the normalized emissions would increase as in Table 3-6. Note that the largest ratio shown (1.10) is still smaller than would have been the case (1/0.8 or 1.25) prior to the shortage.

TABLE 3-6. ILLUSTRATIVE NORMALIZED EMISSIONS OF HYDROCARBON (MILLIONS OF PASSENGER CARS)

Year	Business As Usual (BAU)[b,c]		With Rationing[d]		Normalized Emissions Ratio (With BAU)
	Vehicles	Pollution Units	Vehicles	Pollution[d] Units	
1981	126	126	126	126.0	1.00
1982	129	129	136	132.5	1.03
1983	132	132	146	139.0	1.05
1984	135	135	156	145.5	1.08
1985	138	138	166	152.0	1.10

a. Assumes should-be-retired vehicles use 10% of a normal vehicle's gasoline consumption but pollute 5 times as badly.

b. See footnote a, Table 3-5.

c. Neglects changes in emission standards with time.

d. Assumes that 7 million old cars which should have been retired are kept in the fleet each year. Each of these provides 0.1 x 5 or 0.5 the pollution of an average vehicle; thus, the number of pollutant units increases as if 3.5 million such vehicles were retired per year. The increase in pollutant units is thus 6.5 million per year.

At first sight it would appear that the normalized emissions ratio should be multiplied by the normalized ration rights per vehicle. This would be incorrect, however, because the total gasoline consumption is assumed to be constant, with the average (non-normally-retired) vehicle using more gasoline than its normal "right".

Table 3-6, arbitrary though the numbers are, suggests that the presence of the old vehicles would be only slightly detrimental, and only over the long term. The existence of such vehicles would perhaps increase the tendency to misfuel at-home, but this tendency should, as discussed earlier, be reduced by rationing relative to the non-rationing-with-shortage case.

3.2.4 Gasohol Policies

The Standby Gasoline Rationing Plan (Ref. 6, p. 31) states that fuels that contain ethanol will be included in the rationing plan, but only to the extent of the volume of gasoline in the blend. Thus, only 90 gallons of ration rights would be needed to buy 100 gallons of "gasohol" (which is 10 percent ethanol by volume). Presumably, the provision is intended to encourage production of gasohol, and does not extend to petroleum-based blending agents such as tertiary butyl alcohol (TBA), methyl tertiary butyl ether (MTBE) and other alcohols and ethers now being considered.

Gasohol, as noted above, is a blend of 90 percent unleaded gasoline and 10 percent anhydrous ethanol. Other blends of ethanol and gasoline are, of course, possible and may be marketed in coming years*. Ethanol is not normally used in leaded gasoline, because a principal advantage of the ethanol is to increase octane (in non-premium unleaded grades), a role

* Up to 20 percent anhydrous ethanol is claimed to be acceptable without automotive modification. Also, a stabilized blend, permitting at least some water, known as Hydro-fuel (R) is being or has been promoted.

fulfilled by tetraethyl lead in leaded gasolines.* As refinery equipment in place at any given time can limit production ratio of unleaded to leaded gasoline, this procedure, which artificially stimulates the demand for unleaded gasoline, as the referenced provision clearly does, must be carefully considered.

The argument against this proposal is straightforward: all coupon holders, independent of their cars' nominal needs, would buy gasohol to the extent that it is available.** Supplies, once delivered, would thus be quickly exhausted. The unleaded fuel going into leaded cars, as gasohol, would detract from available unleaded supplies, forcing some disappointed unleaded users to use leaded gasoline or go without. The problem becomes more severe as a bigger percentage of gasohol is marketed. The quantitative significance depends on the ability of the refining industry to respond to changes in demand for leaded and unleaded, on the octane levels of the fuels being marketed, and on how people respond. The following treatment illustrates the problem.

Let

χ_u = the fractional demand for unleaded without rationing.

χ_L = the fractional demand for leaded, without rationing = $1 - \chi_u$.

S_u° = fractional supply of unleaded gasoline, including gasohol, before rationing, = χ_u.†

S_{EtOH} = fractional supply of ethanol, before rationing.

Assume a shortage, f, of hydrocarbons develops, which does not affect the ethanol supply. Assume rationing is imposed.

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*Conventional gasohol may be too low in octane for use in some cars.

**The alcohol, subsidized by various tax relief and incentive provisions, would almost certainly cost less than additional "white market" gasoline.

†The term S_u° is introduced simply for convenience in discussion; as used, it is set numerically equal to χ_u.

Assume also that refiners do not change the ratio of hydrocarbon outputs intended for leaded and unleaded gasolines, and that automotive usage patterns do not change. Assume that available gasohol is delivered to unleaded and leaded cars in the ratio of X_u to X_L.

Under this set of assumptions the unleaded gasoline component in the gasohol used by leaded cars is simply $9 \cdot S_{EtOH} X_L$. Assuming that this material had been expected to be available for unleaded cars, and ration coupons issued accordingly, then unleaded car owners would, in order to receive their ration rights, be forced to buy leaded gasoline in the same volume in order to use their coupons. The total hydrocarbon fuel used by unleaded cars is simply $(S_u^\circ - S_{EtOH})(1-f)$. Taking the ratio, setting $S_u^\circ = X_u$, and rearranging, the fraction* of unleaded cars misfueling (M_f) becomes

$$M_f = \frac{9X_L}{\left(\frac{X_u}{S_{EtOH}} - 1\right)(1 - f)} \qquad (1)$$

Note that this treatment makes no allowance for those drivers choosing to go without rather than misfuel. As such, Eq. 1 provides an upper-bound estimate; however, it is doubted that many would go without and forfeit their coupons. It is felt, in fact, that Eq. 1 provides a not-unrealistic estimate.

The fraction of the total fleet of automobiles which misfuel is the fraction of unleaded cars misfueling times the number of unleaded cars, divided by the fleet size. In terms used here,

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*This is a pure material balance misfueling ratio, lower than and not involving the probabilistic considerations considered in Appendix A. Equation 1 holds only for values of f such that $f \leq 1 - \frac{9}{\frac{X_u}{S_{EtOH}} - 1}$.

the total fraction of cars misfueling, per fueling, is then $M_f X_u$. Some relevant numbers follow in Table 3-7.

TABLE 3-7. PROJECTED FUELS, GASOHOL, AND POTENTIAL MISFUELING NATIONAL AVERAGE

End of Year	X_u [a]	Expected[b] Gasoline Consumption MMBPD	Ethanol Production MMBPD[c]	S_{EtOH}	M_f, f = 0.2	$M_f X_u$
1980	0.45	6.70	0.020	0.00299	0.0414	0.019
1981	0.50	6.57	0.030	0.00457	0.0519	0.0259
1982	0.55	6.43	0.045	0.00700	0.0653	0.0359
1983	0.60	6.30	-	-	-	-

a. Extrapolating data plotted in the *Lundberg Letter*, Feb. 1, 1980.

b. Uses the expected 1980 figure quoted in *Oil and Gas Journal*, p. 68, May 19, 1980, and a 2% per year decline, the latter based on a quote in the newsletter in the same issue, that a 20% decline is expected between 1979 and 1990.

c. *Federal Register*, Vol. 45, No. 101, May 22, 1980, pp. 34854-34855.

According to Eq. (1), as shown in the table, if the ethanol component is not rationed, the fraction, M_f, of unleaded vehicles forced to misfuel (should rationing be imposed in 1981 or 1982) would be, on a nationwide average basis, of the order of 5 to 6 percent. This rate would be per fueling period, assuming that the ratio of gasolines delivered in each fueling period is the same as that for the national totals. *These misfueling rates are very severe numbers.* If, as might be expected, the population forced to misfuel is random, the cumulative fraction having misfueled would increase rapidly with time, as shown in Appendix A. Also, since use of gasohol is more heavily encouraged in some states than in others, the fraction forced to misfuel would vary from place to place. The degree of shortage would also affect the outcome. The effects are illustrated for the end of 1982 time frame in Table 3-8.

TABLE 3-8. ETHANOL-FORCED MISFUELING, CIRCA END OF 1982 AS A FUNCTION OF LOCAL USAGE

X_u	f	S_{EtOH}	M_f	$M_f X_u$	Comment
0.55	0.2	0.005	0.0464	0.0255	
		0.010	0.0938	0.0516	
		0.020	0.1910	0.1054	
		0.0449	0.4500	0.2475	All unleaded is gasohol
0.55	0.3	0.005	0.0531	0.0292	
		0.010	0.1071	0.0589	
		0.020	0.2183	0.1201	
		0.0397	0.4500	0.2975	All unleaded is gasohol

Very high misfueling rates would thus be expected if this policy were pursued in those states which heavily encourage gasohol. Note that if sufficient alcohol exists so that all unleaded is in the form of gasohol, the fraction of unleaded cars forced to misfuel becomes equal to the fraction of leaded cars in the population.

The question naturally arises whether an increase in unleaded could be accomplished by refiners to compensate for the increased demand for unleaded. The required ratio, R, of unleaded hydrocarbon to total hydrocarbons, using the same nomenclature used previously, is

$$R = \frac{9X_L + \left(\frac{X_u}{S_{EtOH}} - 1\right)(1 - f)}{(1 - f)\left(\frac{1}{S_{EtOH}} - 1\right)} \qquad (2)$$

Using the 1982 nationwide figures (Table 3-8) and f = 0.2, R is 0.5825, for a nominal demand X_u of 0.55*, versus 0.547 before the shortage, which may or may not be feasible. The problem

*The ratio of hydrocarbons intended for unleaded/total hydrocarbon is (0.55 - 0.007)/(1 - 0.007) = 0.547.

again becomes more severe as S_{EtOH} increases or as f increases. As an extreme case, with $S_{EtOH} = 0.0449$, $\chi_u = 0.55$, (Table 3-8), the (hydrocarbon to unleaded)/(hydrocarbon total) increases from $\frac{0.55 - 0.0449}{1 - 0.0449}$ or 0.529, to 0.767 with a 20 percent shortage and rationing (Eq. 2). That is, about three-quarters instead of half of the total of the hydrocarbons going into gasoline would need to be brought to an octane level suitable for use in gasohol or unleaded gasoline, under these circumstances.

The foregoing discussion indicates that misfueling may be a severe problem if the ethanol component of gasohol is not rationed, unless the fraction of available gasoline hydrocarbons devoted to unleaded gasoline can be substantially increased, particularly where gasohol has been heavily encouraged. This effect compounds that discussed earlier which suggested a need to increase unleaded to compensate for a shift to high-mpg cars during rationing.

A side effect of this gasohol policy would be a decreased orderliness of the market, as avid purchasers with leaded and unleaded cars alike, rush to buy gasohol. These problems suggest that gasohol should be rationed in precisely the same way as gasoline.

3.3 RELATED ISSUES

3.3.1 Allocation and Prioritization Procedures

During hearings on the proposed gasoline rationing plan, as published December 10, 1979, a lengthy parade of claimants came forth seeking priority allocations of gasoline, should rationing transpire. A significant portion of the planning effort has gone into the weighing of such requests, and some accommodations have been made. These issues are not of direct, or at least evident, significance to this work, and will not be treated here. It is important to note, however, as has been noted previously, that priority usage in a supply-short situation amplifies

the shortage to those who lack such priorities, and will very likely be heavily resented by those not so favored. In a real sense, such prioritization represents a subsidy, providing gasoline more cheaply than it would be available through the "white" market. Businesses having priority uses allotted are doubly favored since purchase of coupons on the white market would likely be written off as a business expense in any event.

These important issues relate to misfueling only to the extent that they affect public perceptions as to equity, and thus to acceptance of gasoline rationing. Little doubt exists that public perceptions are important in determining whether the plan would work, or be violated in numerous ways, some of which could involve misfueling by mechanisms discussed elsewhere in this paper.

Allocation and prioritization procedures are clearly sensitive issues, and must be treated appropriately.

3.3.2 Bifurcated Rationing*

The rationing plan as proposed would allocate gasoline rights per automobile without designation as to type (leaded or unleaded) of gasoline which could be purchased; for convenience this is referred to as a single-coupon scheme. An alternative, which has been proposed as a means to reduce misfueling is to provide coupons labeled according to the type of gasoline which the driver is authorized to purchase; this is termed a "bifurcated" approach, as two classes of rationing coupon would be involved. Two bifurcated schemes are discussed in the following material: In the first, which is the most obvious, the coupons would be labeled "leaded" or "unleaded"; in the second, coupons would be labeled either "unleaded" or "unrestricted", which latter would be provided to leaded car drivers.** In either case,

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* Dr. D. Dacy of IDA and Dr. H. Margolis of M.I.T. contributed important concepts which are incorporated in this discussion.

** A third scheme in which leaded cars would get "leaded only" and unleaded cars would get "unrestricted" coupons is of no interest.

when buying gasoline, even in a self-service station, the attendant would require that the coupon match the gasoline in both type and quantity. Either bifurcated system should greatly minimize misfueling if the gasoline purchaser were permitted to use only the coupons issued to him and the gasoline put in the car for which the coupons were issued (which would probably require putting the car's license number on the coupon itself); misfueling could then be accomplished only by siphoning and bulk transfer of gasoline. In a white market rationing concept in which coupons can be bought, sold, and traded, these restrictions would not apply and the advantages are less clear, and need discussion.

As is the case with a single coupon scheme, bifurcated rationing would impact differently on different groups of drivers. Many such groups might be identified, but the simple grouping shown in Table 3-9 is useful in illustrating possible effects.

TABLE 3-9. PROBABLE EFFECT OF BIFURCATED RATIONING SCHEMES ON MISFUELING, RELATIVE TO SINGLE COUPON SCHEME (see text)

Group	Scheme 1 Unleaded/Leaded	Scheme 2 Unleaded/Unrestricted
I. Owners of unleaded cars only	Reduces (?)	Reduces
II. Owners of leaded cars only*	NA**	NA
III. Owners of leaded and unleaded cars		
A. Unleaded car preferred (best mpg)	Increases	None
B. Leaded car preferred * (best mpg)	NA**	NA

* All vehicle classes affect supply and demand for both fuels and coupons, so indirect effects may result.

** These drivers are more heavily penalized under leaded-short conditions with Scheme 1 than with Scheme 2.

Consider first Group I in Table 3-9, those drivers who own only unleaded cars. This class of drivers, should they wish to misfuel, would be impeded in doing so by either form of bifurcated rationing, since to do so these drivers would need to first acquire coupons allowing them to buy leaded gasoline. This acquisition of coupons would normally involve some time and some expense, as there would probably be a broker's fee and perhaps some price differential between their (issued) unleaded coupons and the leaded coupons which they would need. These transaction costs would serve to dissuade these buyers from misfueling. An uncertainty exists in this statement, however, in that the difference in price between leaded coupons and unleaded coupons is difficult to predict; conceivably, under some circumstances, unleaded coupons could sell for more than leaded coupons, countering the other costs involved, and making it attractive to sell such coupons and misfuel. It is difficult to conceive of unleaded coupons selling for more than unrestricted coupons, however, so that from this standpoint Scheme 2 appears to be preferable to Scheme 1.

The second group of drivers is relevant to the discussion only in that they would represent a source of leaded or unrestricted coupons; this group could, on occasion, use unleaded gasoline but no obvious reason can be seen why they should. This group would be penalized by a deliberate policy of leaded shortage (as suggested elsewhere in this paper), as they would be forced to buy unleaded gasoline when leaded is unavailable; the first scheme would doubly penalize this group should leaded be unavailable, as they would be forced to buy unleaded coupons before they could get gasoline and then pay the extra costs of unleaded.

Group III drivers are those who own (or have in their household) both leaded and unleaded cars; this is probably a fairly large group. Under either bifurcated scheme, these drivers could use leaded gasoline (their ration) in their unleaded car without

undergoing any sort of transaction penalty. Under the first scheme, the sub-group (Group III A) whc maximize their mobility by driving their unleaded car would have, in fact, a significant incentive to do so, as sale of their leaded coupons and purchase of unleaded would take some time and involve some costs. This incentive is eliminated in the second scheme. The final group (III B) of drivers is probably smaller than is Group III A, but would provide some of the unleaded coupons desired by that group.

The above brief discussion indicates some of the complexities which would need to be addressed, along with the costs involved, to recommend for or against a bifurcated rationing scheme. It does appear that the second scheme, in which leaded car drivers receive unrestricted coupons, would be preferable in terms of misfueling potential to the first scheme in which leaded car drivers receive "leaded" only coupons. The second scheme also appears to be superior to a single coupon scheme in terms of misfueling potential, but it would be difficult to estimate the magnitude of this advantage; much would depend on the coupon marketing system, on octane levels, on price differentials, and perhaps on the degree of shortage involved.

3.3.3 Cumulative Misfueling Aspects

As noted earlier, misfueling, at least in principle, can be either habitual or randomly forced, as by shortages of unleaded where leaded is available. Habitual misfueling destroys the catalysts belonging to those misfuelers but the number of such misfuelers is probably more or less constant; random misfueling, however, such as might arise during periods when unleaded is not available and leaded is available involves different individuals each time, so that the number of *exposed* catalysts increases with time. The degree of total damage to the catalysts at any given time depends on the regenerability of the various catalyst parts. This was discussed and modeled at some length in Cutchis et al. (Ref. 2); it has more recently been discussed, and later data presented in Ref. 23. The impact of the issue is noted here and in Appendix A.

Relatively little data is available on regenerability of automotive catalysts. According to EPA, two to four tankfuls of leaded gasoline are needed to permanently destroy a conventional two-way oxidation catalyst pack.* Other sources suggest a much lesser sensitivity;** the differences may lie in the type of catalyst (monolithic or pelleted) being discussed, and very importantly, on whether misfuelings are consecutive or interspersed with proper fuelings. The information available on three-way catalysts is particularly sparse, and somewhat contradictory. Thus, Shelef, Otto and Otto (Ref. 24) state that "three-way catalysts designed to remove simultaneously hydrocarbons, carbon monoxide and nitric oxide in a narrow range of exhaust composition are an example of extreme sensitivity to poisoning....Even the extremely low concentrations of contaminants in current certification fuels have a pronounced effect. Indeed, the success of three-way catalysts is to a large degree predicated on the premise of availability of fuels essentially free of lead." This statement suggests that a single misfueling would be highly detrimental to a car equipped with a three-way catalyst.† However, data from the California Air Resources Board, cited in Ref. 23, imply no significantly greater

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*Per Richard Kozlowski, EPA, May 19, 1980.

**_The Los Angeles Times_, March 12, 1979, cites Charles Gray, Director of Motor Vehicle Emission Control for EPA in Ann Arbor, Michigan, to the effect that a single misfueling causes some damage but recovery occurs to 80 or 90 percent of the original after continued proper fueling; after two tankfuls, recovery is only to 50 or 60 percent; after four misfuelings only 10 percent recovery is possible. (Presumably, this refers to sequential refills.) The same article cites Dr. Fred Bowditch of the Environmental Activities staff of General Motors, "With four or five tankfuls, the catalyst material can be regenerated, but if you use eight or ten tankfuls of leaded gas, one after the other, the catalyst probably is not able to regenerate." See also Cutchis and Oliver (Ref. 2).

†The three-way catalysts are also sensitive to poisoning by sulfur (Ref. 25). Serious questions have also been raised as to the supply of rhodium, a principal active ingredient in these catalysts (Ref. 26). Rhodium comes principally from South Africa and the Soviet Union.

sensitivity for three-way than for conventional oxidation catalysts. Efficiencies and recoveries involved vary with the exhaust ingredient being discussed, i.e., whether hydrocarbons (HC), carbon monoxide (CO), or nitrogen oxides (NO_x) are at issue. NO_x is, of course, reduced only in the three-way catalyst systems.

The differences in cumulative damage between catalysts damaged by a single misfueling and catalysts damaged only by repeated misfueling are very great if random misfueling for a reasonable time period is assumed. This is because the probability that the same individual will be forced to misfuel several times is small. The curves in Fig. 3-2 illustrate the effects, using a cumulative binominal probability model (see Appendix A). Note that if 1 percent of the unleaded cars misfuel each period (i.e., m = 0.01), after 52 fuelings 41 percent of the cars will have misfueled at least once but only 1.6 percent will have misfueled three or more times. The issue is, in fact, very complex. To illustrate, following the Cutchis and Oliver model (Ref. 2, p. 57), those who have misfueled only once will have catalysts with efficiencies ranging from perhaps 50 percent to 90 percent, depending on the number of proper fuelings following misfueling; those who have misfueled twice will have efficiencies ranging from perhaps 25 percent to 70 percent; those who have misfueled three times will have efficiencies varying from perhaps 12 percent to 62 percent, etc. The model cited is based on "conventional" oxidation catalysts (those to which EPA ascribes the need for two to four misfuelings for destruction) and may be inappropriate for more sensitive systems. However, it is clear that if regeneration occurs, as implied by the few data sources available, the consequences of random misfueling are far less serious than would otherwise be the case; i.e., to assume that the number of seriously damaged catalysts is the same as the number of single misfuelings would very likely result in a serious overestimate.

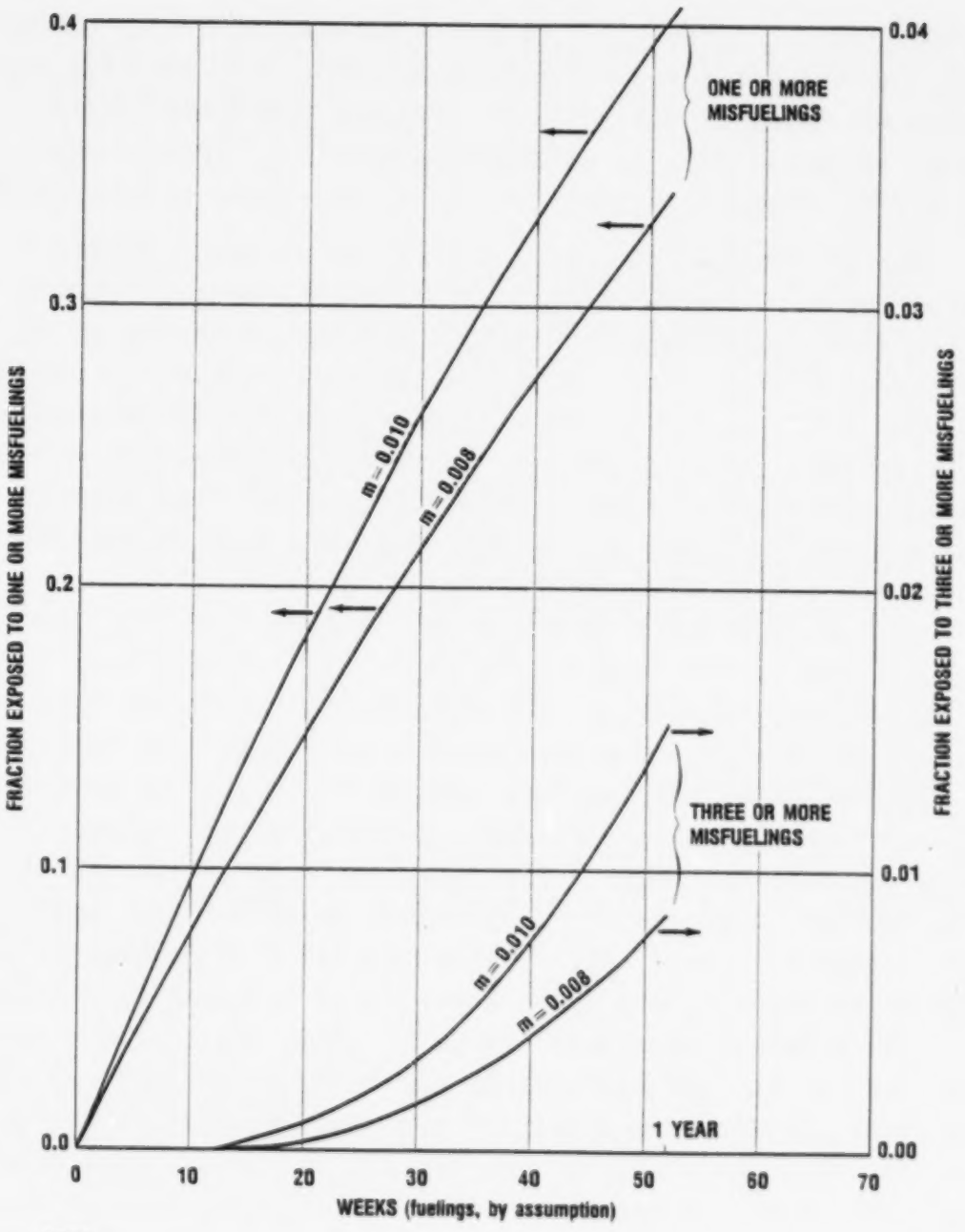

FIGURE 3-2. Cumulative exposures to at least one or at least three misfuelings, for a one-year period at one fueling per week, for two arbitrary misfueling rates.

This issue is not related to rationing other than in terms of its impact should gasohol or other policies, for example, lead to shortages of unleaded gasoline.

3.3.4 Inspection and Maintenance

Inspection and Maintenance (I&M) procedures, wherein the car-driving population fears a forced and expensive catalyst replacement following misfueling, are considered to be effective deterrents to misfueling (see discussion in Ref. 1). Such procedures are expected to be in nationwide use within the next few years. It is of interest to note, however, that a possibly counterproductive aspect of I&M would arise should motorists be forced to misfuel: once forced to misfuel, the motorist might well feel that sufficient damage has been done so that he would be forced to replace his catalyst at the next inspection; under these circumstances he might decide to continue using leaded gasoline, forestalling any catalyst recovery.

It should be noted that I&M procedures, like rationing itself, will be most effective if popularly supported. Should significant numbers of forced misfuelings result from shortages, the perceived inequities associated with subsequent forced catalyst replacement would probably rapidly erode support for the I&M program. Reliance on I&M procedures to prevent misfueling during periods of severe shortages, which are in reality national emergencies, would seem to be unrealistic.

4.0 SOME FINAL COMMENTS

The impacts of a severe and prolonged gasoline shortage on environmental goals developed in more equable circumstances are not easy to foresee; certainly no claim is made that the foregoing treatment is comprehensive. Under some circumstances procedures which could be rejected out of hand under conventional situations might be considered advantageous under extreme shortage conditions. Thus for an area such as Southern California, which is peculiarly vulnerable to air pollution from automotive exhaust, it might be shown that social costs* would be minimized by a policy in which leaded gasoline would be eliminated (or nearly so) from that region, possibly balancing production losses by permitting additional leaded in some less sensitive areas. A policy of this nature is probably not feasible now, but might be feasible once the fraction of leaded gasoline drops substantially below present levels. Alternatively, leaded gasoline might be made available in a declining number of stations.

Finally, it should be recognized that the plan, which received considerable editorial criticism when submitted to Congress,** is to date in effect an outline, with a great deal of detail to be ironed out in further work. Implementation is of course the

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* A point advanced by Professor George Daly, of Houston University.

** As examples, which may or may not be representative, the *Washington Post*, June 16, 1980, entitled its editorial "When the Best Won't Do"; the *Philadelphia Inquirer*, June 18, 1980, included an editorial entitled "The 'best' rationing plan: A Cautionary Horror Tale." The allusion to "best" refers to a quotation from Energy Secretary Charles Duncan that "the plan is the best we could devise," given the constraints (not faced by editorial writers) imposed by Congress.

essence of any action. Given the rather fragile nature of automotive catalysts and the massive national investment involved, it seems clear that the leaded-unleaded issue should be kept in mind in all such implementation planning.

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APPENDIX A

SHORTAGE-INDUCED MISFUELING: ITS MODELING AND PREVENTION

APPENDIX A

SHORTAGE-INDUCED MISFUELING: ITS MODELING AND PREVENTION

A.1 SUMMARY

This Appendix describes exploratory work carried out using a probabilistic approach for shortage-induced misfueling, aimed at an extended period in which all gasolines are in short supply and over which period the fraction of unleaded gasoline sold is increasing. The model assumes that both leaded and unleaded gasoline are delivered to all stations prior to their opening, and cars arrive randomly at each thereafter for fueling. Both classes of users, without leaving the stations, buy their preferred gasoline as long as it is available, but buy the non-preferred fuel thereafter; misfueling occurs only when unleaded gasoline is exhausted first. The model basically assumes that there is no rationing of gasoline. The model could be applicable, however, even if rationing is in use, if there is no specification on the ration coupons as to type of gasoline permitted and if a surplus of coupons exists, so that the holding of a coupon does not guarantee fuel availability.

The assumptions imply desperate circumstances and extreme behavior; the results thus probably represent an upper bound to the forced misfueling problem. It is argued, however, that policies which can be shown to be effective in preventing misfueling under such circumstances should also be effective under less severe conditions. The model is thus applied to several questions of interest.

The model results suggest that shortage-induced misfueling could continue to be a significant problem over the next 5 years or more, even when unleaded gasoline demand rises to 80 percent

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or so of the total, and even if unleaded and leaded gasolines are supplied to service stations in the theoretical demand ratio. An obvious policy to minimize misfueling is thus to impose a *relative deficit* of leaded gasoline; results show that this policy, if it could be implemented, would be extremely effective. (Another policy is suggested which might also be effective, but is not explored; in this, leaded gasoline would be available at progressively fewer stations as the demand diminishes.) The model shows that policies imposing large minimum purchase requirements may be beneficial under certain circumstances and may not be under others. The model indicates that small stations, or stations selling a certain fraction of their (multi-day) delivery of leaded and unleaded gasoline daily, would yield more misfueling than would large stations or stations that simply pump until dry. The model shows further that even with annual inspections and replacement of damaged catalysts, the number of cars on the road having damaged catalysts could *potentially* be fairly large, if supply ratios are such that unleaded disappears first and if catalysts are significantly damaged by a single misfueling. Catalysts tolerant to multiple (preferably at least three) misfuelings would be extremely advantageous under such conditions.

A.2 INTRODUCTION

Misfueling--the use of leaded gasoline in cars designed for use with unleaded--has been noted to arise from differences in cost, performance, and availability (Refs. A.1 to A.3). In this Appendix, focus is on availability, and more specifically on *relative* availability, of unleaded and leaded gasoline, it being assumed that both are in short supply. Prior studies on shortage-induced misfueling have assumed adequate supplies, or at least a relative surplus, of leaded gasoline; this work includes this situation but is more general in its treatment, emphasizing the condition where both gasolines are in equally

short supply or in which, by policy, unleaded is in slight surplus. Also, the potential for misfueling, as the fraction of unleaded gasoline increases with time, is treated specifically here, an aspect not discussed previously.

Performance and price-induced misfueling are not treated here as such. It is argued that individuals who misfuel for these reasons do so habitually; these individuals for this work are included in the ranks of leaded gasoline users. This work is concerned with what is assumed to be a different class of misfuelers--those who misfuel *only* when they find leaded available and unleaded not. Obviously, there may be some who misfuel once due to shortage and then move into the group of habitual misfuelers; the group which is considered here may thus vary in size with time. Such refinements are not addressed.

The time frame implicit in this work is 1980 to 1985. During this period the expected fraction of unleaded gasoline to be sold will increase from about 51 percent in 1980 to 66 percent in 1982, 77 percent in 1984, and 81 percent in 1985 (Ref. A.4).# It is assumed that both leaded and unleaded gasoline will continue to be sold at all stations, when available.

The treatment which follows assumes that gasoline exists in only two forms--leaded and unleaded. It is recognized that stations today offer up to four grades of gasoline, leaded premium (94 AKI**), unleaded premium (91.5 AKI to 93 AKI), leaded regular (89 AKI) and unleaded regular (87 or 89 AKI). Leaded premium, however, appears to be disappearing from the market. If unleaded premium is unavailable, some users might use leaded regular (if 89 AKI) rather than unleaded regular (if 87 AKI). If unleaded regular is 89 AKI, and it is available, there would be little temptation (other than price) to misfuel. For purposes here, however, and without further discussion, it is assumed that the proper split between unleaded regular and

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These are older figures than those cited in the main text, but no consequence ensues.

** AntiKnock Index.

unleaded premium is known and delivered to the market; the important quantities are then the total unleaded gasoline and the total leaded gasoline.

A.3 THE SCENARIO

The period is assumed to be one in which gasolines of all types are in short supply. A service station operator is this model gets a shipment of gasoline (leaded and unleaded) while the station is closed. He chooses to make this shipment last for some number of days or openings, dividing the shipment accordingly so that the same amount of gasoline of each type is sold each period. Rationing may be in effect but the coupons do not specify the type of gasoline and more coupons than gasoline may exist.* Flags are put up when a certain grade of gasoline is exhausted but motorists are in line, and do not leave simply because their preferred gasoline is exhausted. The operator, to avoid trouble as gasoline sells out, permits a self-service mode to exist while he busies himself with preparations for the station closing. He has noted that on occasion, the leaded disappears first, and cars calling for leaded use unleaded; at other times, the opposite happens, but over the course of the week the shipment balances demand reasonably well and he again orders the same ratio of leaded and unleaded from the jobber: he may change his order slightly periodically as he recognizes an increasing demand for unleaded. He rationalizes also on the misfueling question that only a few cars misfuel each time (for the first time), and feels that the problem (which is not his) is thus not of much significance.

The scenario implies difficult circumstances and behavior patterns which may not be encountered; i.e., a user of unleaded

*The current rationing plan does not specify fuel type. Delays in deliveries of crude oil or other factors (summer vacations, etc.) could reduce supplies below those expected, leading to a surplus of coupons. Coupons might also be counterfeited.

may decide when unleaded is gone, to wait for the next opening (or find another station) and yield his place in line to the user of leaded gasoline, which may still be available. Nevertheless, the assumption that misfueling will take place under these circumstances allows for simple modeling and provides an estimate of the *potential* for misfueling; it is argued that a policy which largely prevents shortage-induced misfueling under this assumption should also be effective should motorists behave more responsibly.

The model follows.

A.4 THE MODEL

The problem, as posed, is a statistical one. Cars are assumed to arrive randomly at the hypothetical gas station, at times exhausting leaded first and at other times exhausting unleaded first, this latter case being the only one which can lead to misfueling. If the number of cars fueled per opening is reasonably large ($\tilde{>}$ 30) a Gaussian distribution can be used (instead of a binominal distribution), permitting ready use of statistical procedures. To simplify matters, each car, whether leaded or unleaded, is assumed to call for one unit of gasoline. Under these circumstances, the expected number* of misfuelers, E, for a Gaussian distribution, for each fueling period is:

$$E = \frac{1}{\sqrt{\sigma 2\pi}} \int_{F}^{N} (\chi - F) e^{-\frac{(\chi - U)^2}{2\sigma^2}} d\chi \,, \qquad (A.1)$$

*The author is indebted to Dr. I.W. Kay of IDA for help with this treatment. Helpful suggestions by P. Cutchis are also acknowledged.

where

$\sigma = \sqrt{Npq}$.

E = the expected number of shortage-forced misfuelers, per N cars fueled, when summed over a large number of events or stations.

p = the fraction of cars in the automotive population calling for unleaded.

q = 1-p is the fraction of cars using leaded gasoline (including habitual misfuelers).

F = the units of unleaded gasoline to be sold during the open period.

N = the total number of cars fueled, and by assumption, the total number of units of gasoline to be sold, per open period.

χ = the number of cars calling for unleaded which arrive at any given station per opening.

U = the number of cars which can be provided unleaded gasoline during the open period.

Misfueling occurs only when, by chance, χ exceeds F, i.e., when the number of cars calling for unleaded exceeds the amount of unleaded to be sold. Note that in this model the "shortage" does not enter directly; if some fraction, y, gets no gasoline during the fueling period, then those cars quite obviously cannot misfuel.

The expected number E of misfuelers is per N cars. However, the fraction of cars which call for unleaded is Np. Thus, the fraction of cars which can misfuel, and which do misfuel, m, per fueling, is simply

$$m = \frac{E}{Np} (1-y) , \qquad (A.2)$$

where m is the fraction of cars which misfuel per visit and y is the fraction of cars which get no fuel at all.

The assumption is made in Eq. (A.2) that the cars getting no fuel are distributed in the same fashion as cars in the general population. For the rest of this work, however, y, since it is unknown, will be assumed to be zero. This assumption is in line with the rest of the model, which in large measure provides an upper bound estimate in any event.

For the usual case, where the operator tries to order the gasoline he thinks he will need, F = U, in which case Eq. (A.1) has the simple solution:*

$$E_{F=U} = \sqrt{\frac{Npq}{2\pi}} \qquad (A.3)$$

and

$$m = \frac{E}{Np} = \sqrt{\frac{1-p}{2\pi Np}} \qquad (A.4)$$

It is important to note that m is not zero, even though the delivered unleaded gasoline fraction is equal to the unleaded car fraction. Other observations can also be drawn from Eqs. (A.3) and (A.4). Before doing so it is important to note that m is the fraction of cars which misfuel, *each fueling period.* The total fraction of cars which have misfueled builds up with time. It is this cumulative effect which is of concern. If a single misfueling significantly damages a catalyst, then the fraction (m_{cl}) of catalysts so damaged increases according to**

$$m_{cl} = \sum_{i=1}^{n} m\,(1 - m_{cl,\,i-1}) \qquad (A.5)$$

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* As shown later, a term has been dropped which is of no significance unless $p \gtrsim 0.95$.

** If the initial condition involves no exposed catalysts, m_{cl} is simply $1 - (1-m)^n$.

where n is the number of fuelings, and $m_{c1,\ i-1}$ is the cumulative fraction of catalysts with at least one exposure to lead just prior to the ith fueling.

In later discussion, to show the important effects of catalyst sensitivity, the term m_{c3} is introduced, where m_{c3} is the cumulative fraction of catalysts exposed to three or more misfuelings. Both m_{c1} and m_{c3} (and others) are available in tables of the cumulative binominal probability function (Ref. A.5).

While the service station operator may prefer the case where F = U, refinery limitations or government policy may force him to purchase some other split. The more general solution (Eq. A.6) of Eq. (A.1) then applies:

$$E = \frac{\sigma}{\sqrt{2\pi}}\left(e^{-\frac{1}{2}\left(\frac{F-U}{\sigma}\right)^2} - e^{-\frac{1}{2}\left(\frac{N-U}{\sigma}\right)^2}\right) - \frac{F-U}{\sqrt{2\pi}} \int_{\frac{F-U}{\sigma}}^{\frac{N-U}{\sigma}} e^{-\frac{z^2}{2}}\, dz \quad (A.6)$$

where the integral is a standard tabulated function.

Note that in Eq. (A.3) for the F = U case, the term

$$e^{-\frac{1}{2}\left(\frac{N-U}{\sigma}\right)^2}$$

was dropped. The term is always negligible in cases here. Note also that Eqs. (A.4) and (A.5) are still applicable, with E evaluated from Eq. (A.6)

These questions are applied in the following section.

A.4 MODEL APPLICATIONS

A.4.1 Station Size Effects, Unleaded Gasoline Fraction Matched to Unleaded Car Fraction

Equations (A.3) and (A.4) can be used to show for the F = U case, how the expected number of misfuelers, E, and the expected fraction of misfuelers, m, vary with the number of cars served, N, and the fraction of unleaded cars in the population. Some results are given in Table A.1.

Note that the fraction of misfuelers decreases as N increases; large stations are thus preferable to small. It follows that if a daily allocation approach is used, the operator should pump a fraction of his total gasoline each day rather than a fraction of each type of gasoline per day. Note also that the expected number is always a maximum at p = 0.5, but the maximum is very flat; the fraction of unleaded cars misfueling drops, however, with increasing p. Nevertheless, if no other measures are taken, the potential for misfueling clearly exists even to 1985 ($p \cong 0.8$) and beyond.

TABLE A-1. POTENTIAL MISFUELING (PER FUELING) AS AFFECTED BY UNLEADED CAR RATIO (p) AND NUMBER OF CARS SERVED (N). UNLEADED GASOLINE FRACTION = UNLEADED CAR FRACTION (F = U)

	N = 100		N = 500		N = 1000	
p	$E_{F=U}$	m	$E_{F=U}$	m	$E_{F=U}$	m
0.1	1.20	0.120	2.68	0.0535	3.78	0.0378
0.2	1.60	0.080	3.58	0.0357	5.05	0.0253
0.3	1.83	0.061	4.09	0.0273	5.78	0.0193
0.4	1.95	0.049	4.36	0.0219	6.18	0.0155
0.5	1.99	0.040	4.45	0.0178	6.31	0.0126
0.6	1.95	0.033	4.36	0.0146	6.18	0.0103
0.7	1.83	0.026	4.09	0.0417	5.78	0.0083
0.8	1.60	0.020	3.58	0.0089	5.05	0.0063
0.9	1.20	0.013	2.68	0.0059	3.78	0.0042

The number N to be chosen is not certain. According to Ref. A.6, the average U.S. station pumps 46,300 gallons per month. If this average station is open weekdays only (22 days per month) some 2,100 gallons per day are pumped. If the station is open, say, twice a day, then some 1,050 gallons are pumped per opening. At 8 gallons per car this corresponds to 130 cars. This model (Table A.1) would then show great potential for misfueling. [For N = 100 and p = 0.5, with F = U, 4 percent of the cars using unleaded gasoline (excluding habitual misfuelers) would misfuel each period.] The operator may, however, not ration each class of gasoline on an opening-by-opening basis, making N much larger. A typical delivery is 8,000 gallons,* which if pumped without being subdivided, would service some 500 to 1,000 cars; the average future delivery is, of course, unknown. At any rate, while the number N is critical to quantitative evaluation, it is less critical to the illustration of policy choices. For purposes of further discussion, an N of 500 seems reasonable and will be used. It must be recognized, however, that lower values of N may occur, so that from this standpoint the model results may not be "upper bound" as suggested earlier.

A.4.2 Cumulative Damage Aspects (F = U)

Turning now to cumulative aspects, assume the number of damaged catalysts is initially zero in the population considered. Equation (A.5) can be used to show how rapidly affected catalysts would build up. As values of $p < 0.4$ are now of no interest, these cases are dropped. Table A.2 shows the results for a number of cases of interest. For orientation, one fueling per week might be reasonable; hence the number of fuelings roughly equals the number of weeks.

*P. Cutchis, private communication, January 1980, per discussion with operator.

TABLE A-2. FRACTION (m_{cl}) AND NUMBER (E_{cl}) OF CATALYSTS AFFECTED (E_{cl})* PER 500 CARS; UNLEADED GASOLINE FRACTION = UNLEADED CAR FRACTION; N = 500

			13 Fuelings		26 Fuelings		52 Fuelings	
p	E	m	m_{cl}	E_{cl}	m_{cl}	E_{cl}	m_{cl}	E_{cl}
0.4	4.36	0.02185	0.2496	49.9	0.4370	87.4	0.6850	136.6
0.5	4.45	0.01784	0.2086	52.2	0.3738	93.5	0.6078	152.0
0.6	4.36	0.01457	0.1737	52.1	0.3172	95.2	0.5338	160.0
0.7	4.09	0.01168	0.1416	49.6	0.2632	92.1	0.4572	160.0
0.8	3.58	0.00892	0.1100	44.0	0.2078	83.1	0.3724	149.0
0.9	2.68	0.00595	0.0746	33.6	0.1437	64.7	0.2667	120.0

*Exposed to at least one misfueling.

Obviously, by this model the cumulative damage would increase towards 100 percent of the cars if the shortages continued indefinitely. Annual inspections would presumably keep cumulative exposures, on the average, to perhaps 52, some cars having more and some less. This point is discussed further later. The main message of Table A.2 is that significant *potential* exists for catalyst damage, even with annual inspections and as unleaded cars and unleaded gasoline reach levels of 80 percent or more.

A.4.3 The More General Case: Deficits and Surpluses of Leaded

The catalyst destruction rates discussed above, if encountered, would clearly be unacceptable. However, these are for the market-balanced case where F = U; that is, the fraction of unleaded gasoline delivered is equal to that "demanded" by the fleet at large. The more general case is also of interest, as given by Eq. (A.6) and as plotted in Fig. A-1.

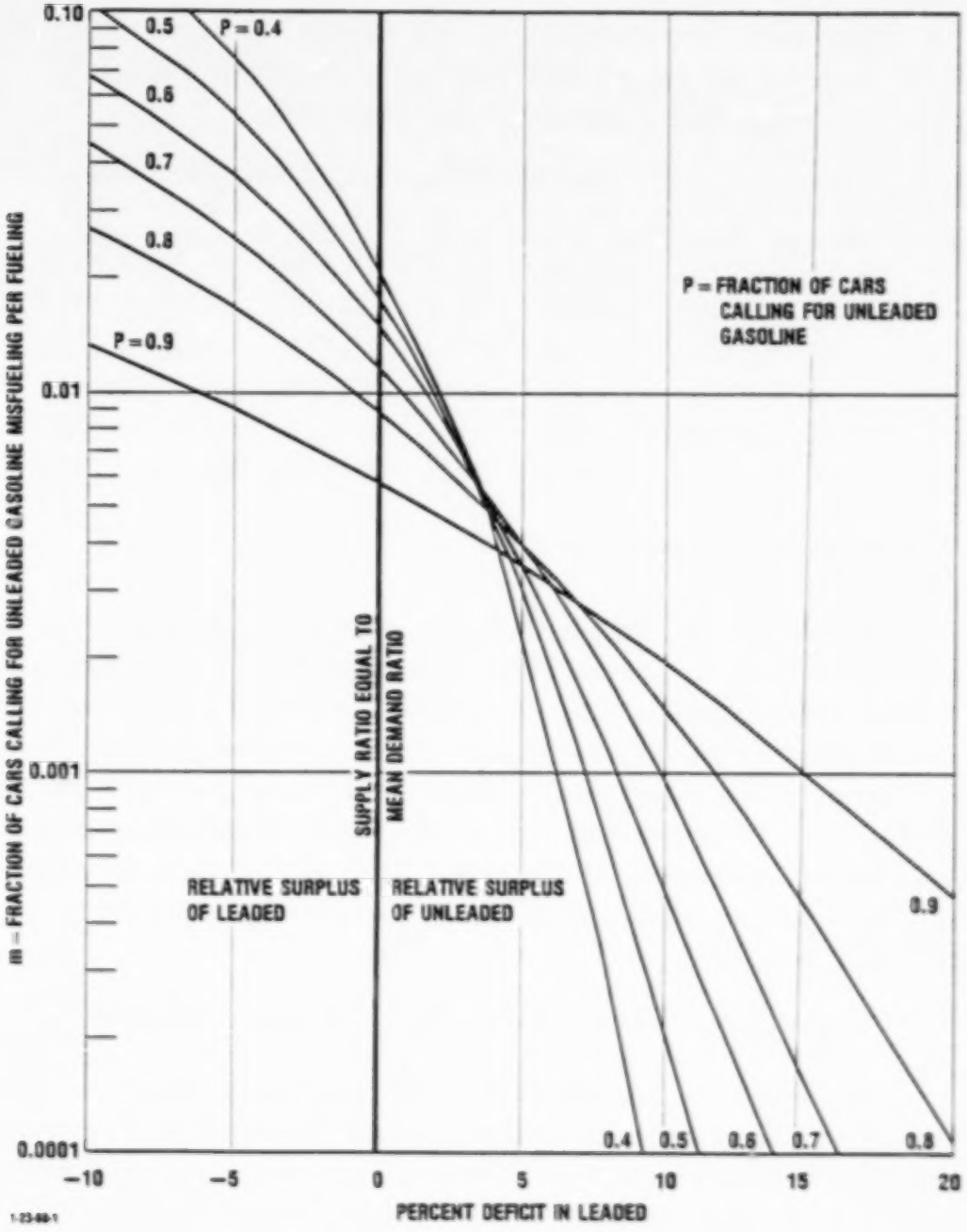

FIGURE A-1. Misfueling fraction, per fueling, as a function of supply ratios (percent deficit in leaded) and fraction of cars calling for unleaded gasoline, per model, for N = 500.

The ordinate in Fig. A-1 is the fraction of unleaded cars misfueling due to shortages, per fueling. The abscissa is the deficit of leaded gasoline, referenced to the F = U case. The assumption is that, through government policy or refinery limitations, the service station operator, throughout the U.S., is always forced to take some different ratio of unleaded to leaded gasoline than called for by theoretical demand (possibly locally evaluated). A "5 percent deficit" of leaded thus implies that 5 percent less leaded gasoline is delivered than called for, with this deficit in volume being upgraded in clear octane and added to the unleaded pool. For example, if 60 units of unleaded and 40 units of leaded are theoretically needed (i.e., p = 0.6), a "5 percent deficit", as used here, means that 38 units of leaded and 62 units of unleaded are delivered. A "negative deficit", as on the left side of the vertical line in Fig. A-1 is based on the same reference; a 5 percent negative deficit means that, for the same population of cars, 42 units of leaded and 58 units of unleaded would be delivered.

Note in Fig. A-1 how rapidly the expected fraction of misfuelers drops as it becomes more difficult to get leaded than unleaded fuel. Thus if N = 500, the deficits in Table A.3 reduce the misfueling rate, m, to 0.001 or 1 per 1000 unleaded cars, per fueling.

TABLE A-3. LEADED DEFICITS YIELDING A MODEL MISFUELING RATE OF 0.001, FOR N = 500

p	Required Deficit, %
0.4	6.0
0.5	7.1
0.6	8.3
0.7	9.8
0.8	11.7
0.9	15.0

The deficits required are extremely sensitive to N (and vary with p), with larger values of N greatly minimizing the degree of deficit necessary to keep m to any specified value. This is because of the $e^{-\frac{1}{2}\left(\frac{F-U}{\sigma}\right)^2}$ term in Eq. (A.6) in which the exponent is linear in N for a given imposed deficit. Thus the exponent is five times as large for N = 500 as for N = 100.

For increasing "negative deficits" (moving to the left of the zero line), the fraction of misfuelers rapidly approaches the fractional deficit. Thus at p = 0.6 and 10 percent "negative deficit," the surplus of leaded is (1 - 0.6) (0.10) or 4 percent, and the fraction of misfuelers is simply 0.04/0.6 of 0.67, about equal to the plotted number; the expected number of misfuelers per fueling is, per Eq. (A.6), simply U = F.

It is not known whether deficits such as those suggested by Table A.3 can be achieved by the refiners or imposed by government policy. If F = U, or deficits in unleaded exist, it appears that catalysts, if sensitive to single misfuelings, will continue to be in danger. There are, of course, other alternatives. One superficially appealing policy, which has not been pursued, is to make leaded gasoline available at fewer and fewer stations as time passes. "Leaded only" stations might also be considered. Enforcing the closing of stations when they run out of unleaded should also be considered.

A.4.4 Catalyst Deactivations and Costs in the Presence of Fuel Shortages and an I&M Program

An effective inspection and maintenance (I&M) program tends to have a powerful effect on misfueling rates, as motorists greatly prefer to avoid the large expenditures associated with catalyst replacement. However, in a period of extended shortage, such conventional economic factors would become less effective, although how much less so is unknown. In any event, the foregoing model again permits the calculation of a limiting

case, in which such economic considerations are neglected entirely. The first assumption is made that, if cars are inspected annually, and effects are roughly linear with time, the "average" catalyst age of all cars on the road is 6 months; in the second, in estimating annual replacement costs, the appropriate catalyst age is clearly 1 year. In applying the model, the previous examples will be extended, with the fraction of unleaded cars on the road increasing from 40 to 90 percent. An average fueling rate of once per week is assumed, as is an annual inspection period. Two questions become at issue. The first is what effects such misfueling may have on air quality; the second is the cost to consumers of replacing damaged catalysts. Available evidence suggests that a single misfueling, followed by proper fuelings, has minor effect on catalyst efficiency (see Ref. A.3 and discussion in main text); the damage resulting from several such sequences depends on the catalyst and on the number of proper fuelings between misfuelings. The number of catalysts which might be ordered replaced under an I&M program depends on the sensitivity of the testing procedures; analytical tests for lead could be performed which would easily detect a single misfueling. The possibility thus exists that the number of catalysts to be replaced could be based on the number of single-time misfuelers, whereas the air-quality effects should be based on a much smaller number of multiple misfuelers. Both numbers are thus of interest: the single misfueling case will be considered first. Some results follow, in Tables A.4 and A.5, assuming 500 cars per station, and either balanced supply-demand ratios or an adjusted deficit of leaded gasoline, corresponding to Table A.4.

Note (Tables A.2 and A.4) that for balanced supply and demand ratios the number of cars on the road with catalysts exposed to at least one misfueling can be large, approximately 20 to 40 percent of the fleet, even with annual inspection. Similarly, in Table A.5, costs are high and again greatly reduced

TABLE A-4. CARS ON THE ROAD WITH CATALYSTS DAMAGED BY A SINGLE MISFUELING. (PER MODEL)
ANNUAL I&M, 26 FUELINGS, N = 500

Fraction Unleaded Cars	Potential Misfueling Per Fueling	Potential Cumulative Fraction Damaged	Potential, Damaged Catalysts, Millions*
		Case 1. F = U (Table A.2)	
0.4	0.02185	0.4370	17.5
0.5	0.01784	0.3738	18.7
0.6	0.01457	0.3172	19.0
0.7	0.01168	0.2632	18.4
0.8	0.00892	0.2078	16.6
0.9	0.00595	0.1437	12.9
		Case 2. Scheduled Deficit of Leaded Gasoline (Table A.3)	
0.4	0.001	0.0257	1.03
0.5	0.001	0.0257	1.29
0.6	0.001	0.0257	1.54
0.7	0.001	0.0257	1.80
0.8	0.001	0.0257	2.06
0.9	0.001	0.0257	2.31

*Assumes 10^8 Light-Duty Vehicles (LDV).

by the assumed scheduled leaded gasoline deficit. With an imposed scheduled deficit of leaded gasoline (Case 2), the numbers are greatly reduced.

The above results apply to catalysts damaged by a single misfueling. As discussed above, the annual cost results might be applicable, even if three or more misfuelings are required to substantially deactivate a catalyst, if a single misfueling could be picked up by a sensitive inspection station, and replacement ordered. However, if, for illustration, three misfuelings are required to permanently damage a catalyst, and the misfuelings are random events, the cumulative number of damaged catalysts is greatly reduced, as shown by the comparison for arbitrary values of m in Table A.6.

TABLE A-5. POTENTIAL MISFUELING-INDUCED CATALYST DESTRUCTION AND REPLACEMENT COSTS.
ANNUAL INSPECTION PROGRAM. 52 FUELINGS.

(N = 500)

Fraction Unleaded Cars	Potential Misfueling Per Fueling	Cumulative Fraction Damaged	Catalysts Replaced Millions*	Estimated Annual Costs, Billions*
		Case 1. F = U (Table A-2)		
0.4	0.02185	0.6830	27.3	8.2
0.5	0.01784	0.6078	30.4	9.1
0.6	0.01457	0.5338	32.0	9.6
0.7	0.01168	0.4572	32.0	9.6
0.8	0.00892	0.3724	29.8	8.9
0.9	0.00595	0.2667	24.0	7.2
		Case 2. Scheduled Deficit in Leaded (Table A-3)		
0.4	0.001	0.0507	2.0	0.6
0.5	0.001	0.0507	2.5	0.8
0.6	0.001	0.0507	3.0	0.9
0.7	0.001	0.0507	3.5	1.1
0.8	0.001	0.0507	4.1	1.2
0.9	0.001	0.0507	4.6	1.4

*10^8 LDV assumed and $300/catalyst replaced.

TABLE A.6. CATALYST FRACTIONS EXPOSED TO ONE AND THREE MISFUELINGS

		26 Fuelings		52 Fuelings	
m	$P_{F=U}$*	m_{c1}	m_{c3}	m_{c1}	m_{c3}
0.020	0.4431	0.4086	0.01475	0.6503	0.08593
0.015	0.5859	0.3249	0.00678	0.5443	0.0433
0.010	0.7609	0.2300	0.00219	0.4070	0.01535
0.008	0.8326	0.1884	0.00116	0.3414	0.00845
0.001	**	0.0257	2.56×10^{-6}	0.0507	2.13×10^{-5}

*Equation (A.4)
**Scheduled deficit of leaded

A relatively minor (but tedious to evaluate) third point is also involved in estimating the number of "damaged catalysts," if three misfuelings rather than one are required for "damage." This is related to the fact, illustrated in Fig. A-2, that at small values of m the buildup in m_{c1} with time is nearly linear, so that a 26-week mean life may not be inappropriate. The buildup in triple misfuelers (m_{c3}) is, however, not linear being very low at early times, so the mean value to take is by no means obvious; both the distribution of travel miles (variations in number of fuelings) and the buildup in time would need to be accounted for.

The point to be made here is not the complexity of the problem but the greatly reduced number of catalysts which would need replacement if three misfuelings rather than one are required before catalysts need replacement and misfueling is a random process.

A.4.5 Effects of Increasing Minimum Purchases

If supply-demand rations (F = U) are balanced, effects of imposing larger minimum purchase requirements are straightforward. Two effects are involved; on the one hand, N is decreased, so that the expected fraction of cars misfueling

$$\left(\sqrt{\frac{1-p}{2\pi Np}}\right)$$

increases per fueling period; on the other hand, the number of fueling periods between, say, annual inspections decreases. The effect is illustrated in Table A.7 by comparing cumulative (m_{c1}) catalyst damage after 52 fuelings with 500 cars served per station to cumulative exposures after 26 fuelings with 250 cars served per station. The reduced number of fuelings is beneficial, as would be expected. This is because a decrease in N (the number of cars served per gasoline station supply period) increases m, the fraction of cars which misfuel, but the number of fuelings per calendar period (assuming constant consumption rates) also changes; the cumulative effect

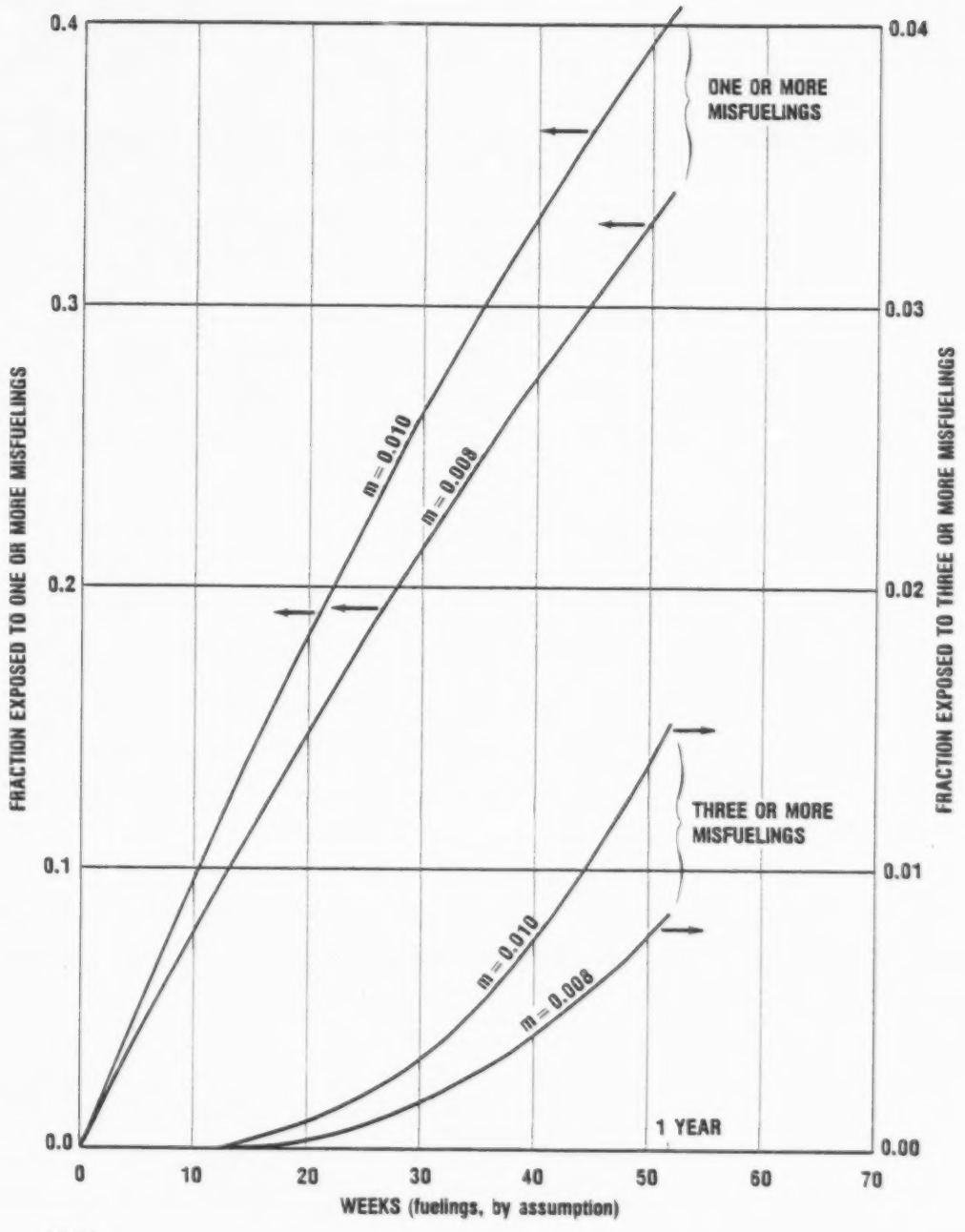

FIGURE A-2. Cumulative exposures to at least one or at least three misfuelings, for a one-year period at one fueling per week, for two arbitrary misfueling rates.

TABLE A-7. EFFECT OF DOUBLING OF MINIMUM PURCHASES. N = 500 PRIOR TO DOUBLING (F = U)

	500 Cars Served, 52 Fuelings		250 Cars Served, 26 Fuelings	
p	m	m_{cl}	m	m_{cl}
0.4	0.02185	0.6830	0.03090	0.5578
0.7	0.01168	0.4572	0.01652	0.3515
0.9	0.00595	0.2667	0.00841	0.1972

on catalyst exposure then decreases with increases in the minimum fill volume. (If catalysts have a tolerance for lead which varies with lead content of the gasoline, which they very likely do, the problem is obviously much more difficult.)

If a policy which imposes a relative deficit of leaded gasoline is in effect, the conclusion appears to differ, at least if the deficit is held constant, as shown in Table A.8. A full range of cases has not been considered. This different result enters from the powerful effect of N on E when F > U (Eq. A.6). A cross-over may exist at some degree of leaded deficit where the same damage results, even if the average purchase is doubled.

TABLE A-8. ILLUSTRATION OF CHANGES IN CUMULATIVE MISFUELING WITH DOUBLING OF MINIMUM FUEL PURCHASES, SCHEDULED DEFICIT.

		500 Cars Served 52 Fuelings			250 Cars Served 26 Fuelings (Alternate Periods)		
p	Leaded Deficit, %	E	m_1	$m_{cl,\,52}$	E	m_1	$m_{cl,\,26}$
0.4	6.0	0.200	0.001	0.0507	0.470	0.00470	0.1153
0.7	9.8	0.350	0.001	0.0507	0.589	0.00336	0.0838
0.9	15.0	0.450	0.001	0.0507	0.582	0.00258	0.0650

A.4 COMMENT

The foregoing model has, as noted, certain assumptions in it which almost certainly result in high absolute estimates of misfuelings. Calibration of the model against past observation is probably not feasible, because past shortage situations were not of the chronic and rather extreme character assumed in the model, but the general implications of the model are not unreasonable and are probably correct. A relative shortage of leaded gasoline would *a priori* be expected to reduce misfueling and a surplus should increase it. The advantages of hard-to-destroy (several misfuelings required to deactivate) catalyst packs are clear.

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APPENDIX B

RATIONING WORKSHOP ATTENDEES

May 19, 1980

APPENDIX B

RATIONING WORKSHOP ATTENDEES

May 19, 1980

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Professor Henry Steele
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Mr. Ephraim King
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